Smart Glove:

An Assistive Device to Enhance Recovery of Hand Function

During Motor Rehabilitation

by

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A Thesis Presented in Partial Fulfillment
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Master of Science

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ABSTRACT

Stroke accounts for high rates of mortality and disability in the United States. It levies great economic burden on the affected subjects, their family and the society at large. Motor impairments after stroke mainly manifest themselves as hemiplegia or hemiparesis in the upper and lower limbs. Motor recovery is highly variable but can be enhanced through motor rehabilitation with sufficient movement repetition and intensity. Cost effective assistive devices that can augment therapy by increasing movement repetition both at home and in the clinic may facilitate recovery. This thesis aims to develop a Smart Glove that can enhance motor recovery by providing feedback to both the therapist and the patient on the number of hand movements (wrist and finger extensions) performed during therapy. The design implements resistive flex sensors for detecting the extensions and processes the information using the Lightblue bean microcontroller mounted on the wrist. Communication between the processing unit and display module is wireless and executes Bluetooth 4.0 communication protocol. The capacity for the glove to measure and record hand movements was tested on three stroke and one traumatic brain injured patient while performing a box and blocks test. During testing many design flaws were noted and several were adapted during testing to improve the function of the glove. Results of the testing showed that the glove could detect wrist and finger extensions but that the sensitivity had to be calibrated for each patient. It also allowed both the therapist and patient to know whether the patient was actually performing the task in the manner requested by the therapist. Further work will reveal whether this feedback can enhance recovery of hand function in neurologically impaired patients.

DEDICATION

This thesis is dedicated to my parents, sister and grandmother for their endless love, support and encouragement. My parents have been the most important mentors of my life. They have always encouraged me to consider every day as an opportunity to showcase my best. They advised me to never give up on my dreams, to be honest and to work closely on challenges related to my passion. I have only achieved success following their words of wisdom. I have a lot to learn from my sister who is very optimistic and energetic and believes in enjoying life to the fullest without compensating on a great career. My grandmother has been a great pillar of support with her daily prayers for my wellbeing. I owe my success greatly to the endless blessings she has showered on me.

ACKNOWLEDGEMENTS

I take this opportunity to express the greatest appreciation to my committee chair, Dr. Jeffrey Kleim, who has the perspective and character of a genius: he consistently conveyed a spirit of adventure and enthusiasm in regard to research and teaching. He never set boundaries for innovations and ensured that I got the best possible resources for implementing my thesis. Without his guidance and persistent help, this thesis would not have been a success.

I would like to thank my committee members, Dr. Marco Santello and Dr. Christopher Buneo, for their valuable suggestions during the review sessions. Your support and encouragement is greatly appreciated.

In addition, a thank you to Dr. Jeffrey Labelle for his valuable suggestions related to improvisation of my thesis. I would be failing in my duty if I don’t extend my greatest gratitude to Dr. Mark Spano for always finding time in between his busy schedule and assisting me in building the circuit for the thesis.

I also extend my sincere thanks to the authorities of Swan Rehabilitation Clinic and Banner Good Samaritan Rehabilitation Out Patient Clinic for providing me the invaluable opportunity to test my device on the stroke patients seeking rehabilitation therapy.

My thesis would not have been successful without the cooperation extended by the stroke patients who participated in the study. They showed great patience and kindness in trying out the first prototype of the medical device I developed in spite of the inadequacies it had.

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ABBREVIATIONS

ARAT	Action Reach Arm Test
AWG	American Wire Gauge
Contd.	Continued
DC	Direct Current
Etc.	Et cetera
I/O	Input/ Output
IDE	Integrated Development Environment
K Ohm	Kilo Ohm
ms	Milliseconds
ml	Milli liter
PC	Personal Computer
V	Volts
XL	Extra Large

CHAPTER 1

INTRODUCTION

Stroke is a loss of neural tissue caused by reduced blood flow or bleeding within the brain. It is the fifth leading cause of death in the United States, affecting more than 795,000 every year (Centers for Disease Control and Prevention n.d.). Although there has been a steady and significant reduction in the incidence of stroke over the past century, mortality rate still remains high killing almost 1 out of 20 stroke victims every year (Centers for Disease Control and Prevention n.d.). Stroke is also one of the leading causes of long-term disability in the country.

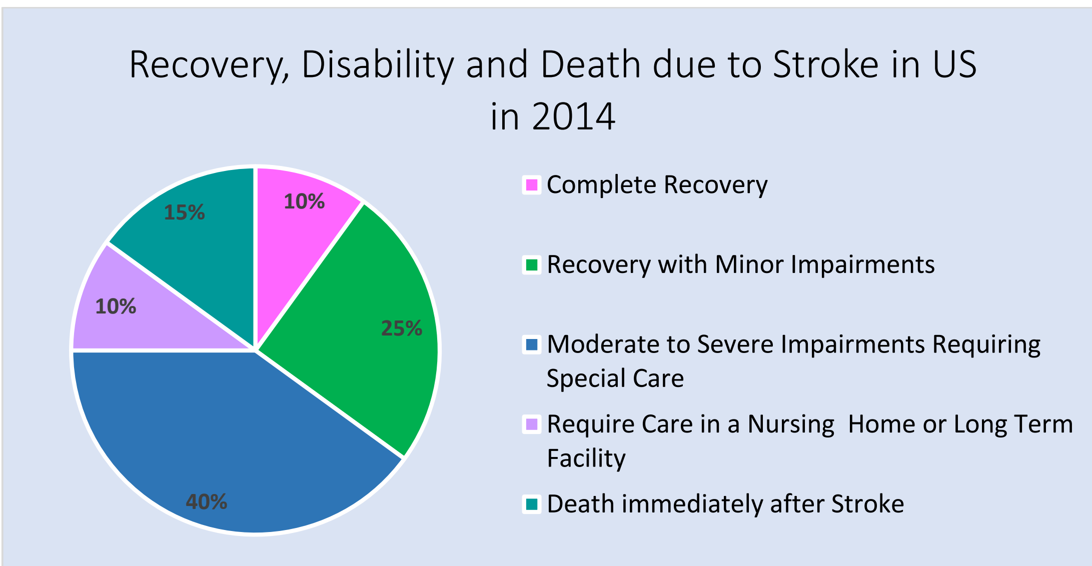


Figure 1. Recovery, Disability and Death Due to Stroke in 2014(Go et al. 2013)

There are currently over 7 million stroke survivors of which 66% will have lifelong motor impairments costing the United States approximately $36.5 billion every year (Go et al. 2013).

Currently, the only accepted treatment for stroke is rehabilitation. The aim of rehabilitation is to help stroke victims to achieve the maximum level of independence and productivity, but recovery is highly variable. Indeed, rehabilitation and recovery is a lifelong process and the neurobiological substrates and parameters of effective rehabilitation interventions are poorly understood. The importance for finding effective treatments is further magnified by the fact that the average life expectancy of the general population is increasing leading to a dramatic increase in the number of stroke survivors over the next few decades.,

Outpatient rehabilitation programs are being considered as a good alternative to the more expensive hospital based programs. Still the costs associated with outpatient rehabilitation programs are high and often outside what medical insurance will cover. A study was conducted to capture the direct costs for outpatient rehabilitation services and medication for 54 first time stroke survivors for the years 2001-2005 at The University of Texas Health Science Centre (Godwin et al. 2011). The results highlight the significant costs incurred by patients for the first 12 months after discharge from an inpatient rehabilitation setting. The average cost for outpatient rehabilitation and medication for the first year after discharge was $17,081. Out of this, the average yearly costs for medication and rehabilitation were estimated to be $5392 and $11,689.

Stroke and Motor Impairments

Understanding and estimating the extent of disability affects the quality of rehabilitation provided to stroke survivors. Therapists need to understand the factors that influence recovery and use quantifiable results from the therapy to effectively stage patients during the recovery process. Many conceptual models of disability have been developed to understand, assess and measure the extent of disability. In United States, Nagi model is commonly used by researchers to describe the consequences of stroke at the body, person and society levels (Jette 2009).

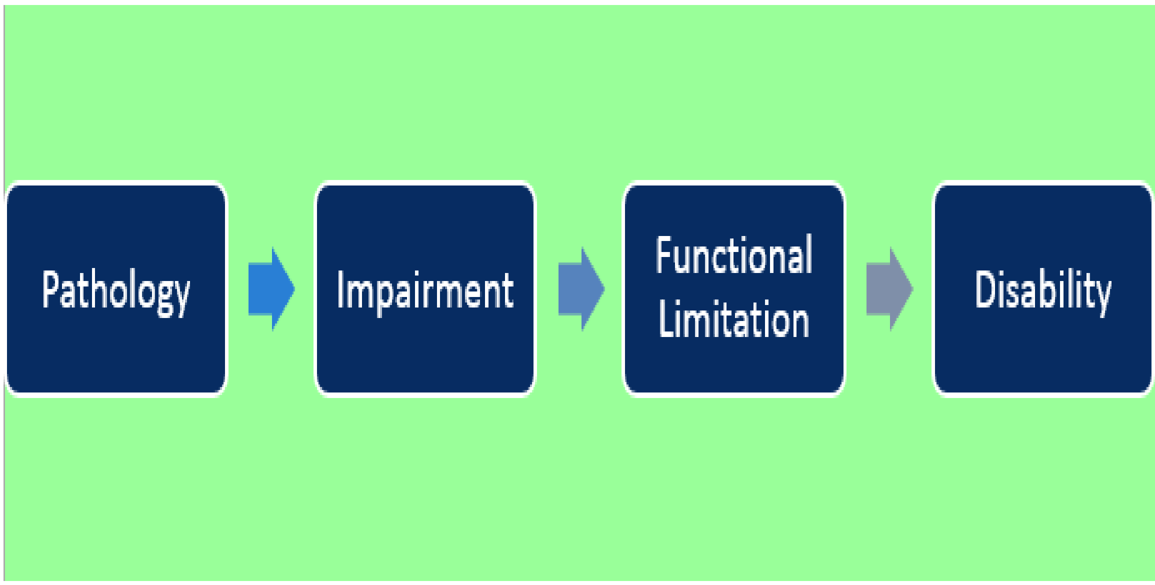


Figure 2. Nagi Model of Disabling Process (Duncan 1994)

According to Nagi's model, impairment is a physiological or psychological consequence of a disease. Common stroke impairments are motor dysfunction, aphasia, cognitive deficits and depression. Functional limitations are consequences arising from the impairments caused. A good example of functional limitation after stroke is the difficulty faced by patients in walking and transfer. Disability refers to the societal consequences arising from the functional limitations. In case of stroke, disability can refer to issues like the inability of a patient to maintain good relationship with family and perform leisure activities. The extent of disablement can be reduced if effective recovery therapy is initiated immediately after the occurrence of stroke. Hence the impairment phase is the most critical phase.

It is difficult to estimate the exact nature of disability after stroke as the outcomes or reviews from patients are collected at different times during which quality of treatment, method of therapy etc. would have changed. Still there are few studies that have been framed to understand the nature of disability after stroke and the timeframe for which it persists. Bonita et al. (1988) conducted a 1 year community based study on recovery of motor function after stroke in 680 stroke patients (Bonita and Beaglehole 1988). The proportion of stroke survivors with motor deficits dropped to 71% after 1 month to 62% after 6 months. The results throw light on the long periods of time that are required for substantial recovery from motor impairments. Studies conducted by the researchers at The University of Manchester on 135 acute stroke patients showed that even at the end of one year, 30% of the patients remained dependent and required continuing rehabilitation therapy for motor impairments (Andrews et al. 1981).

Thus, stroke remains to be one of the medical conditions that is a leading cause of long-term motor impairment among the affected population. Timely and effective rehabilitation is the key to a speedy recovery.

Limitations of Current Rehabilitation Plans

Motor learning occurs through extensive practice during which performance feedback is used to develop skilled movement. Motor improvement after stroke can be thought of as a relearning process and this notion can be used in developing stroke rehabilitation therapies. However, most current therapies fail to provide the repetition, intensity and feedback required to facilitate such relearning.

Currently, stroke patients spend less than quarter of a day performing rehabilitation activities at the therapy centers (De Wit et al. 2005) (Bernhardt et al. 2004). The mean rehabilitation therapy session time is 49.5 minutes, ranged between 24 and 64 minutes (Kaur et al. 2012). Bernhardt et al. (2004) observed the involvement of 58 patients in stroke recovery therapy for the first 14 days after admission to the acute stroke care unit (Bernhardt et al. 2004).

Patients were found to interact with their therapists and involve in therapy only for 5.2% of the working day which amounts to 0.5 hours of the 9 hour observation period. In a study of group therapy sessions for stroke rehabilitation, Thompson et al. (2009) observed that in an in-patient rehabilitation facility, stroke patients were involved in therapy only for 1.2 hours out of the 11 hour observation period (Thompson and McKinstry 2009).

Lang et al. (2009) investigated the amount of movement practise involved during stroke rehabilitation over 312 therapy sessions in 7 rehabilitaton sites (Lang et al. 2009). For upper extremity, the mean number of repetitions of functionally effective movements were 32 per session (Average session time: 36 ± 14 minutes). Ideally, a stroke rehabilitation therapy should average 3 hours per day for 7 days a week (Lowry 2010). Thus, more intensive stroke rehabilitation therapy having optimum duration needs to be delivered for attaining speedy functional recovery.

Rehabilitation Therapy in Animals

Extensive research has been conducted to implement stroke and rehabilitation models in animals and translate them into human models. Mostly rats are used to study stroke in comparison to pigs and non-human primates. This may be due to the similar branching of blood vessels and nerves in humans and rats (Yamori et al. 1976), relatively lower costs of rodents (Durukan and Tatlisumak 2007) and the availability of various behavior assessments to measure the functional outcomes (Schaar et al. 2010). Rats are great assets in forelimb rehabilitation studies as they have limb movements that have immense similarity with humans (Whishaw et al. 2002).

Studies in animals consistently show significant improvements in motor function after stroke yet similarly impressive results are rarely observed in clinical studies. A comprehensive analysis of controlled clinical trials for acute ischemic stroke in the 20th century was performed by Kidwell et al. (2001). A total of 178 controlled clinical trials involving 73, 949 patients were identified. Most of the trials were pharmacological in nature and only 3 of them met the conventional criteria for a positive result (Kidwell et al. 2001). The reasons for the vast differences in recovery rates in animal versus human studies are many. Animals fail to show spasticity and depression, and do not have many of the comorbid factors observed in human patients such as coronary disease, diabetes and other age related health issues. Further, clinical studies rarely incorporate sufficient repetition, intensity, challenge and motivation into rehabilitation (Kleim 2012). If the therapy fails in the ideal conditions observed in animals, there is a lesser probability of it being a success in more complex human models

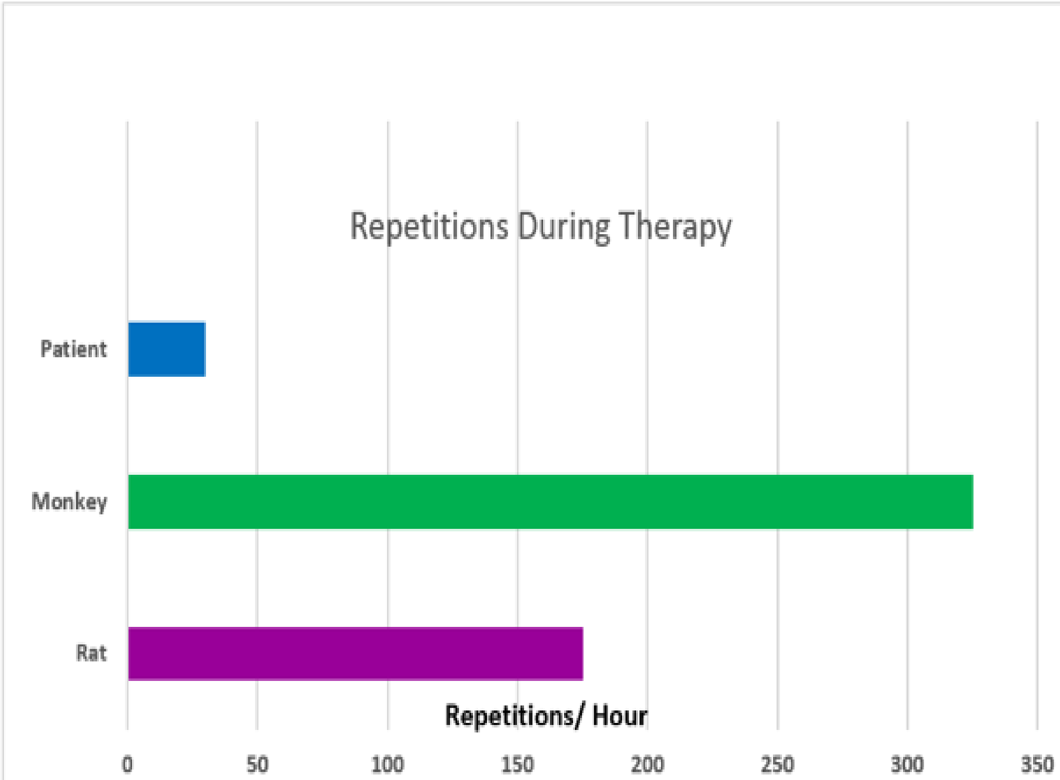


Figure 3. Number of Repetitions Performed by Animals in Pre-Clinical Studies and Human Stroke Patients during Standard Rehabilitation (Kleim 2012)

Figure 3 shows the great difference in the average number of repetitions performed every hour in rats, monkeys and human stroke patients. In animals, it is very easy to drive these behavioral signals as in most of the studies, the animals are food deprived and lack any activity throughout the day apart from the activities performed to obtain food during the behavior assessment sessions. So, the animals are highly motivated during the sessions and perform hundreds of repetitions in a very short period of time. As a result, the impaired limb in animals is used much more than in human stroke patients, which results in better functional improvement after therapy sessions.

Elevating Functional Improvement Levels in Humans

Lang et al. (2010) conducted a group study to check whether stroke patients can be motivated enough to perform challenging tasks with higher number of repetitions in shorter intervals of time (Birkenmeier et al. 2010).

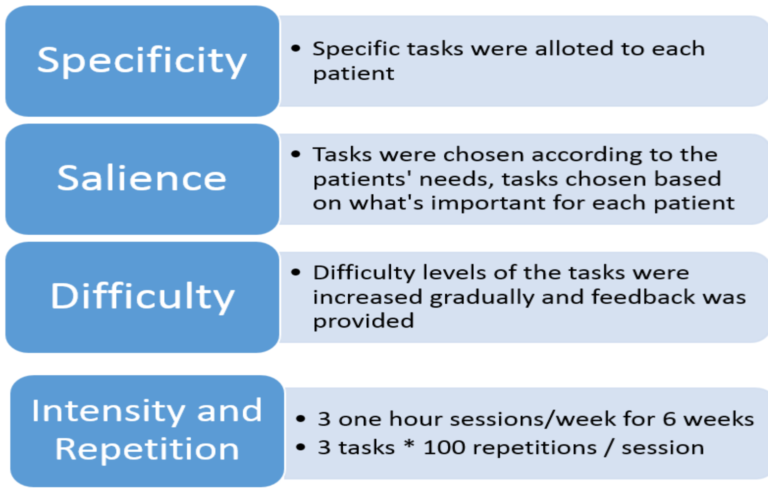


Figure 4. Driving Key Behavioral Signals during Therapy Sessions in Patients with Upper Extremity Stroke (Birkenmeier et al. 2010)

15 patients with upper extremity stroke underwent 6 weeks of 1 hour high-repetition therapy sessions (3 sessions/week for 6 weeks) where they were challenged to perform 300 repetitions (3 tasks * 100 repetitions) in every session. Tasks were wisely chosen to drive maximum number of behavioral signals that can initiate neural plasticity. The patients showed improved ARAT scores which directly correlated with the increase in the number of repetitions.

Thus higher doses of movement practice with informative feedback is required in humans to accelerate neural plasticity that can enhance functional improvements.

The Importance of Feedback and Motor Recovery

Functional improvement after stroke is a complex process and so is the response of stroke patients to therapy. One of the important requisites for an outcome measure is the detection of its change over time. In stroke therapy, an important outcome measure can be the feedback on performance of the patient over subsequent therapy sessions. Dobkin et al. (2010) conducted an international randomized clinical trial to investigate the role of session feedbacks in optimizing motor learning after stroke (Dobkin et al. 2010). 179 patients with unilateral lower extremity stroke participated in the study and during inpatient rehabilitation session, once a day, they were given feedback about their average walking speed. During discharge, the mean walking speed improved by .46m/s from the baseline for patients for whom feedback was given. For the rest of the patients, it increased only by .25m/s. Thus, the study highlights the fact that feedback about performance in therapy sessions can enhance motor learning during rehabilitation.

While the specific form of therapy that any individual patient receives is highly variable, both animal and human studies have shown that there are key factors required in order for rehabilitation to be effective. These include repetition, intensity, challenge and motivation (Kleim and Jones 2008). Despite the importance of these factors, in many rehabilitation clinics they are rarely considered resulting in suboptimal treatment (Kleim 2012). The goal of this thesis is to develop an inexpensive and easy to use glove that provides patients and therapists with feedback on the number of wrist and finger flexions performed during therapy in order to increase movement repetition and intensity during therapy.

The goal of this thesis is to develop a device that can provide feedback to both patients and therapists to enhance movement repetition and ultimately promote motor recovery in the wrist and fingers.

The number of wrist and finger extensions performed during therapy can be a good feedback for the doctors and patients as the therapy mainly focuses on increasing the number of these extensions performed. This can be achieved by performing the therapy wearing a glove fitted with sensors to detect these extensions. The thesis revolves around the design of such a glove and analysis of its effectiveness in improving motor recovery from spasticity of wrist and fingers in stroke patients

CHAPTER 2

RESEARCH OBJECTIVE

The aim of the study is to develop a Smart Glove that can serve as an assistive device and provide feedback while performing stroke rehabilitation therapy both at home and hospital.

Measured wrist and finger extensions are used to quantify hand movements. The glove wirelessly communicates with a computer or smart phone and hence is portable. It can be programmed to provide feedback on the fine motor movements performed during therapy in any setting. The fine wrist and finger extensions can be measured using resistive flex sensors attached to the glove and sensitivity can be adjusted according to the unique requirements for each patient. In the feedback, the number of wrist and finger extensions performed along with the time elapsed during the session is provided, enabling a measure of intensity.

Significance of the Study

The design components of the glove are carefully chosen to achieve the requirement of minimum cost with optimum functionality. Currently, the finger and wrist extensions performed during stroke therapy are not counted at either of the two rehabilitation clinics visited. Providing a feedback on the extensions performed can greatly help therapists and patients to progressively increase repetition and intensity during therapy. The restricted and unique hand movements of stroke patients makes the distinction and recording of these extensions by mere observation very difficult. The glove is programmed to detect these extensions using the resistive flex sensors attached to it. This reduces the ambiguity and human error related to recording of the actual number of these fine extensions performed. The device is also expected to improve the performance of stroke patients over successive sessions through the feedback it provides. In addition, the system will allow the therapist and patient to know whether the patients are making the desired movements or not.

Scope and Limitations

The study will focus only on recording the number of wrist and finger extensions recognized above a sensitivity level during the therapy sessions.

The sensitivity level can be adjusted for every patient depending on the nature of their disability. The amount of the smallest detectable extension is limited by the sensitivity of the sensor. The sensor is unidirectional and is programmed to detect only the initiation of the extension.

The device is compatible only with computers having Windows and Mac operating systems and phones or tablets having Windows, Apple and Android operating systems.

The device is powered by a portable 3V coin battery and the battery drains out after every half an hour of operation. The battery needs to be replaced after this.

Conceptual Framework

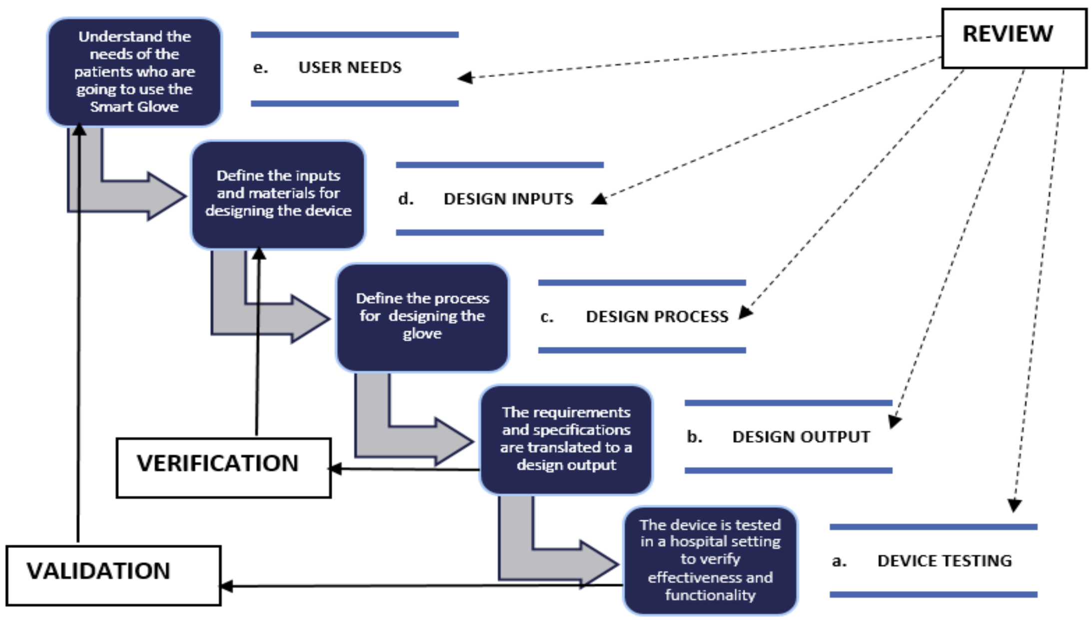


Figure 5. Conceptual Framework for Smart Glove Design

Figure 5 indicates the steps to be followed to build and test the Smart Glove. The design steps are in compliance with the standard waterfall model suggested by FDA for medical device design (Center for Devices and Radiological Health n.d.).

Design Input and Output Verification

Once the device inputs are collected and the input requirements reviewed, the process of translating these requirements into a device design starts. Every design input is translated to a new design output. The design output is conformed to meet the design input requirements and this becomes a design input for another step in the device design. Hence this type of verification is an iterative process.

Design Reviews

Design reviews are conducted at critical points in the device design cycle. They provide assurance that a phase has been completed in a required manner and that the next phase can begin.

User Needs and Final Device Validation

Design validation encloses design verification and extends the evaluation to check whether the devices are in actual compliance with the user needs.

CHAPTER 3

DEVICE DESIGN

Understanding User Needs

It is very important to capture the user needs at an early stage in the project as they are the precursor to design inputs. Design inputs capture quantifiable and objective details about the device design. Hence it is critical to have a set of clearly defined user needs.

The main questions to address while defining the user needs are:

Who are the primary users of the device?

As the thesis goal clearly states, the Smart Glove is to be used by stroke patients undergoing rehabilitation therapy for motor recovery from spasticity in the wrist and hands. The device will be tested for its effectiveness and functionality on suitable stroke patients at the Swan Rehabilitation Clinic and Banner Good Samaritan Rehabilitation Out Patient Clinic in Phoenix.

How is the patient going to interact with the device?

The patients are going to perform therapy wearing the Smart Glove fitted with resistive sensors. The glove will record the number of extensions performed and time elapsed during the session. This information will be gathered by a chip mounted on the wrist and wirelessly transmitted to the computer where a report can be generated at the end of the session.

What kind of components will the device use?

The device will detect the different types of extensions performed and time elapsed during the therapy session using a microcontroller that is embedded in the chip. A program is burned into the microcontroller that implements an algorithm to detect the initialization of an extension by measuring the change in sensor values. This information is communicated wirelessly to the computer and displayed simultaneously on the screen.

What kind of environment will the device be used in?

The device is intended to be used in a rehabilitation setting and provides feedback to both the therapist and patient. We tested our device at the Swan Rehabilitation Clinic and Banner Good Samaritan Rehabilitation Out Patient Clinic. However, the device is intended to also be used in the home by patients and care givers.

Is the device safe and effective?

The device is safe to use as there is no current or voltage interaction with the body. It is not causing any changes to the structure or composition of the user's body. The effectiveness of the device will be determined by testing it on stroke patients when they are performing rehabilitation therapy.

Are there any explicit requirements that need to be considered for the users of the device?

As the device will be used by stroke patients having restricted mobility of hands, the design should make sure that the difficulty in performing wrist and finger movements is not enhanced during therapy. This can be ensured by choosing a suitable material and generic design for the glove.

Are there any restrictions and requirements on the cost of the device?

The device should be able to give meaningful feedback to stroke patients at minimal cost as one of the goals of the thesis is to develop a design that is portable and that can significantly reduce the costs incurred in outpatient rehabilitation for upper limb spasticity. This can be achieved by the wise choice of design components without compensating on the functional effectiveness of the device.

Definition of Design Inputs

Material of the Glove

Polyester is a good fit for the material of the glove. Polyester gloves are widely used in consumer and industrial applications, so they are readily available in the market in various sizes and colors. As polyester is a type of polymer that can be easily manufactured, it is inexpensive. In addition to the market related advantages, polyester gloves are very thick and flexible. It provides a reliable platform to mount circuit components as circuit elements can be easily stitched to the exterior of the glove. This also will shield the hands of the user from being in contact with the circuit, preventing itching, rashes and irritation. Due to its flexibility, the material will stretch and contract sufficiently to provide a snug fit. Polyester is also porous, facilitating required ventilation to the hands in spite of providing a snug fit. It has good sweat absorption properties making it suitable for use in long therapy sessions. Being a good insulator, the material will be immune to the current and voltage leaks in the circuit.

Type of Glove

Figure 6. Schematic of Customized Cycle Glove Fitted with Velcro Straps

Because the glove will be used by stroke patients, it needs to be easily wearable and removable. It should give enough ventilation and should provide maximum exposure to fingers and wrist for unrestricted movement. A polyester fingerless cycle glove will comply with these specifications. The glove has a wide base and it can be adjusted to rightly fit the wrist using Velcro straps. Parts of the glove that cover the fingers are made of porous synthetic rubber to facilitate ventilation. Additional Velcro straps can be easily stitched to the generic design to make a customized design. In addition, the glove also has padding in the palms to enhance absorption which can be very helpful in long therapy sessions.

Type of Sensor

A sensor should be able to record an event and provide a corresponding output that is measurable and meaningful in itself or an output that can be converted to another form that is measurable. There are different types of sensors that can be used to detect extensions in fingers and wrist. Pressure sensors, resistive sensors and accelerometers are capable of measuring joint movements by detecting the changes in pressure, resistance and rotation. Unrestricted movements of the hand while wearing the glove and cost effectiveness are two important design requirements that will help greatly in narrowing down the choices of an appropriate sensor for the design. The stroke patients should not be having enhanced difficulty in using the glove because of the circuitry mounted on the glove. Hence the sensor should be light and flexible.

Resistive flex sensors meet all the requirements. They are strip sensors that change their resistance proportional to the amounts to which they are bent. These strips are made of carbon loaded polyethylene with a copper laminate attached on one side to provide flexibility during bending. The design incorporates FS7548 model manufactured by

Sparkfun and the sensor is 4.5 inches in length. The length of the sensor is suitable for detecting the extensions when attached to gloves of various sizes. Also the sensor is thin and flexible to snugly fit against the joints. As the resistance increases when the sensor is flexed, the initiation of extension can be detected by the constant decrease in resistance over a timeframe. The sensitivity of the sensor is limited by its bend resistance range (60K to 110 K Ohms). In addition, since the strip is made from inexpensive material, it is available for low prices in the market. The design incorporates two strip sensors for independently detecting the two types of extensions.

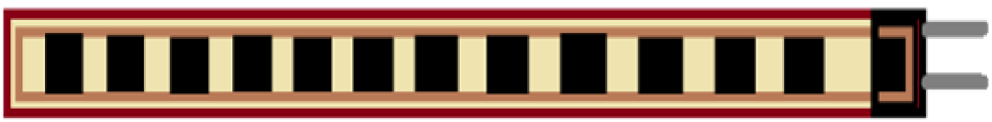


Figure 7. Schematic of the Resistive Strip Sensor Implemented in Smart Glove

Processing Unit

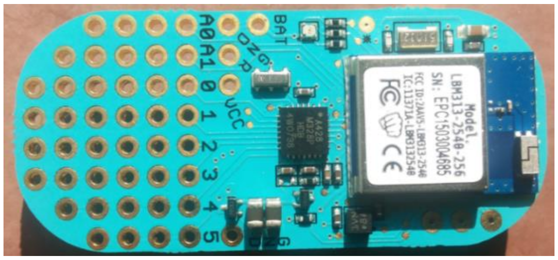


Figure 8. Lightblue bean: Processing Unit of Smart Glove

An appropriate processing unit should be able to capture the sensor values and convert it to a meaningful digital output that can be incorporated in a program. The program then implements a logic to detect the extensions. Microcontrollers that come as integrated circuits having a processing unit, memory and input/output peripherals are a good choice for a control unit that requires lesser data processing and more interfacing between hardware and software systems. The control unit should be light and small so that it can be mounted on the wrist without restricting the hand movements during therapy.

I have incorporated the Lightblue bean manufactured by Punch Through Design as the control unit in the Smart Glove. It is a microcontroller mounted on a board that has a perf board attached to it. Circuit components are required to convert the resistance values generated by the sensor to digital voltage values that can be interpreted by a software program. These circuit elements can be soldered onto the perf board. The perf board points are electrically isolated from each other. So the circuit components can be soldered in any convenient pattern. Also, the board comes with a low energy Bluetooth module that communicates with a computer or mobile phone. Even the code can be loaded using the Bluetooth communication protocol. This avoids the need for additional wireless communication and perf board modules which usually leads to complications in ensuring compatibility between the different design blocks. It also increases the overall size of the circuitry which will make it unsuitable for mounting on the wrist. The integrated modules greatly reduce the amount of wiring in the circuitry which facilitates unrestricted movement of hands during therapy.

Programming Software for Lightblue bean

Lightblue bean is a type of integrated Arduino board. Arduino boards are pre-assembled and incorporates open-source hardware and software. Programming is done using the Arduino Integrated Development Environment. The programs are written in C language.

A library named Wiring, makes the input output operations in the IDE very simple. The input/output commands are very user-friendly and implements easy syntax. The program implemented in my thesis was written and compiled using the latest version of the IDE, Arduino 1.6.4 installed in my laptop having Windows 8.1 Operating System. After compilation, the software generates a hex file. It is burned into the microcontroller using a programmer that comes with another software called Beanloader. Beanloader can be associated with the Arduino software using a plug-in and comes with a serial monitor where the therapy session logs can be displayed.

Interfacing with the Display Unit

The control unit communicates with the PC using low energy Bluetooth 4.0 communication protocol. It makes the device portable and a very compact and powerful processing unit. The session logs are displayed in the PC on the serial monitor that comes with the Beanloader software.

High Level Design of the Smart Glove System

The design requirements can be put together to generate a high level design of the system. The data acquisition module comprises of resistive sensors mounted on the Smart Glove. The resistance of the sensors changes according to the amount to which they are stretched while performing wrist and finger extensions. The change in resistance is converted into measurable voltages using the data conversion module. This module comprises of voltage divider circuits having resistors and a constant power supply. The measured voltages are the inputs to the control unit, the Lightblue bean. The bean comes with a microcontroller that takes the analog voltages and converts them to digital values using the inbuilt analog to digital converters. The digital voltage values are then fed into a program that processes the information to detect the wrist and finger extensions.

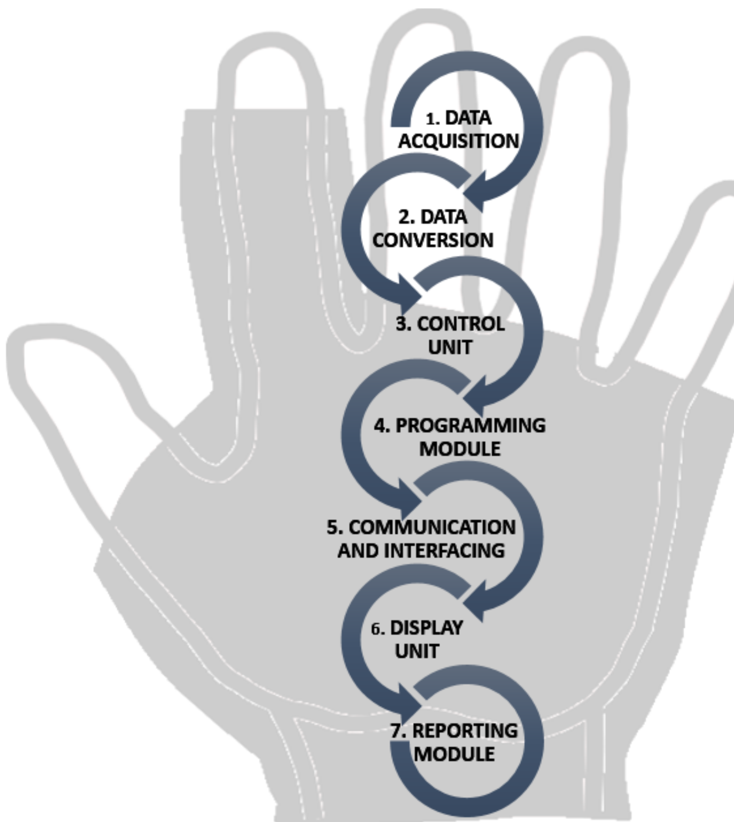


Figure 9. High Level Design of Smart Glove

Programming is done using the Arduino software on my personal laptop. Communication and interfacing between the programming module and control unit is wireless and for achieving this, the Bluetooth communication protocol is implemented. The display unit is the Beanloader software. Whenever an extension is detected, it will be displayed on my laptop, using the serial monitor that comes with the software. Also when the therapy session is completed, a summary is generated having the number of wrist and finger extensions performed along with the time elapsed during the session. The summary can be exported from the serial monitor as a text file. This comprises the reporting module.

Detailed Level Design

Data Acquisition Module

Strip sensors are inserted into pockets stitched on the glove. There are 2 sensors implemented in the design, one for detecting finger flexion, the other for detecting wrist flexion. For detecting finger flexion, the sensor is mounted on the index finger and for wrist flexion, it is mounted on the wrist.

Figure 10. Resistive Strip Sensors Mounted on the Glove Using Stitched Pockets

The strip sensors have very fragile connector pins. These pins are hence soldered to a thick copper conduction wire. The connector pins also exhibit a tendency to detach from the resistive strip during excessive bending. To prevent this, the junction of the connector pins and strip resistor is wrapped in a sponge cushion and held in place using insulation tapes. The resistive sensor is prevented from slipping down from the pockets by attaching Velcro strips to the back of the sponge cushion. A small Velcro strip is also stitched to the glove where the sensor can be attached. Additional Velcro strips are stitched to the base of the glove to attach the wrist sensors.

Figure 11. Cycle Glove with Additional Velcro Strips and Stitched Pockets

Data Conversion Module

The change in resistance of the strip sensors are converted to measurable voltages using voltage divider circuits. Voltage divider circuits break down the supply voltage into smaller voltages over the resistances connected to the supply. The voltages are broken down into smaller components depending on the values of the resistances. The voltage divider circuit in the design implements a 10KOhm resistance in series with the resistive sensor. Output voltage is measured across the strip sensor. When the sensor is extended, its resistance decreases which results in lower voltage drops across the sensor. The extension is detected by this reduction in resistance over time. The power supply for the circuit is provided by the 3V DC pin of the Lightblue bean.

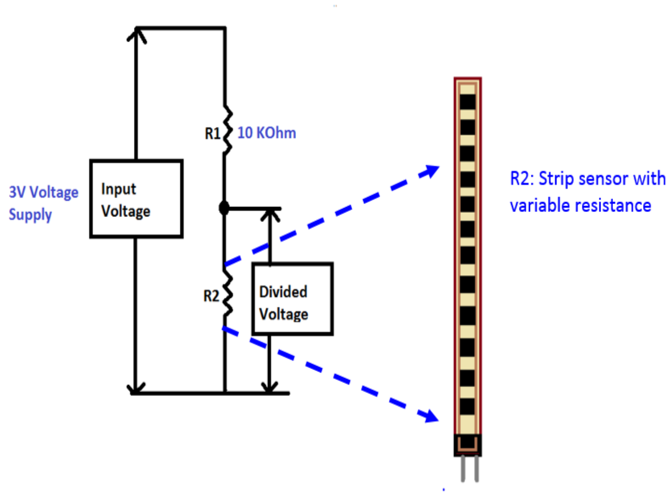


Figure 12. Voltage Divider Circuit for Data Conversion

Control Unit

Lightblue bean is the control unit for the device. It is a low energy Bluetooth Arduino board and has an ATmega 328p microcontroller along with several peripherals to interact with external hardware and software. But Smart Glove uses only the analog pins, digital output pins, ground pins and supply pins of Lightblue bean. It comes with six inbuilt 10 bit analog to digital converters, 2 analog pins, 6 digital input/output pins, one 3V supply pin and 2 ground pins.

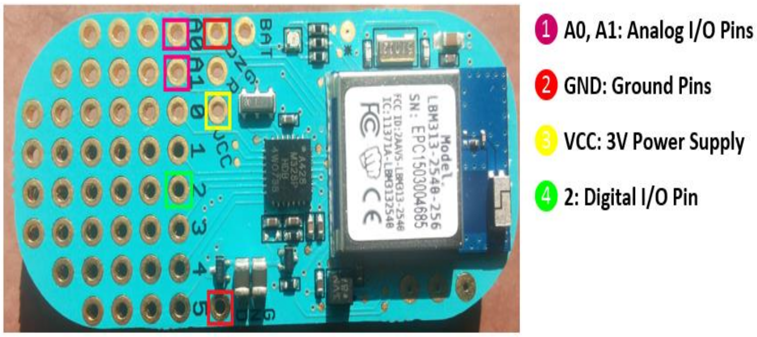


Figure 13. Lightblue bean and Peripheral Pins Used in Smart Glove Design

The bean also has an attached perf board on which the circuitry for data acquisition and conversion can be soldered. The perf board has 34 independent points to which the circuit elements can be attached. It has a 3V operating voltage which is provided by CR2032 coin cell battery attached to the back of the board.

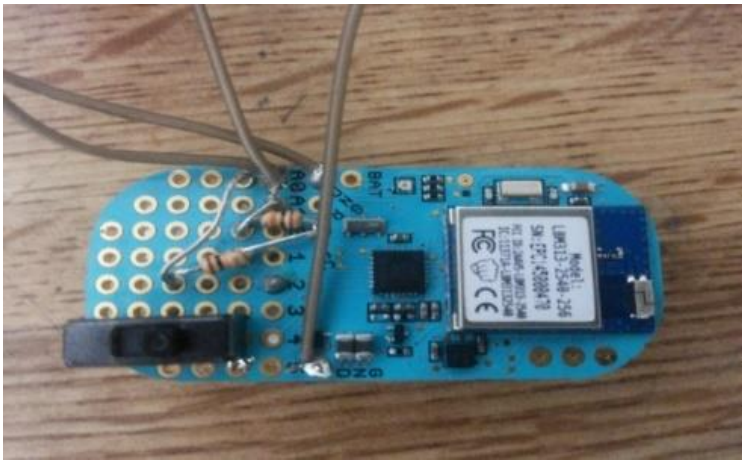


Figure 14. Lightblue bean with Data Acquisition and Conversion Circuitry

Both the sensors are connected across the analog and ground pins. Flexible multifiber wires are used for soldering. These wires are then connected to the thick copper conduction wires that are attached to the sensor pins.

Programming Module

Microcontroller is programmed using Arduino 1.6.4 IDE. The resistances of the strip sensors are converted to voltages. The analog voltages are then converted to digital values ranging from 0 to 1023. The program monitors these digital values for both the sensors every 250 ms.

Initiation of an extension can be detected by the continuous decrease in the digital voltage values and a count is maintained for both wrist and finger extensions. The program starts only when the sliding switch is on, which can be recognized by the high state of digital pin 2. From then on, it implements the logic to detect the different types of flexions in loops until the slide switch is off. This is characterized by the low state of digital pin 2.

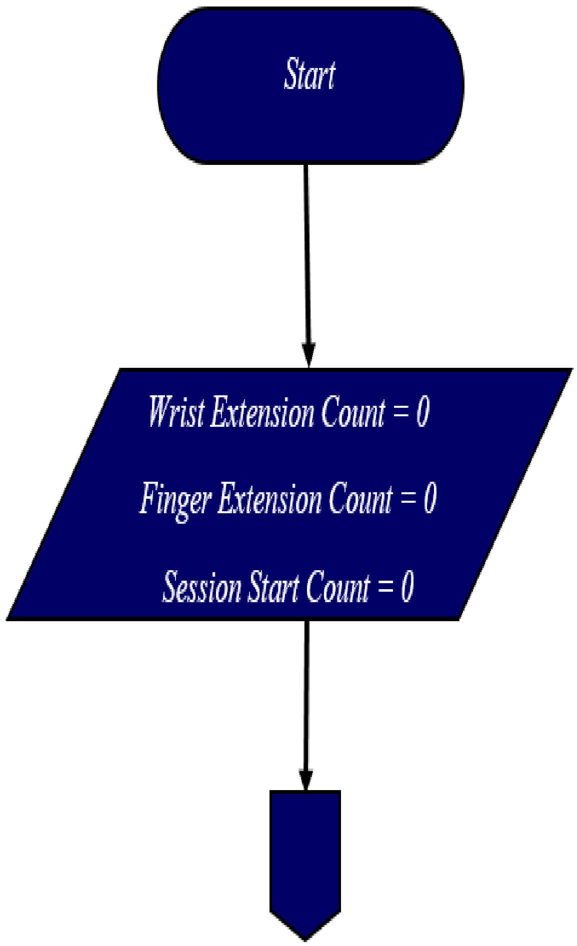


Figure 15. Process Flow of the Microcontroller Program to Detect Wrist and Finger Extensions

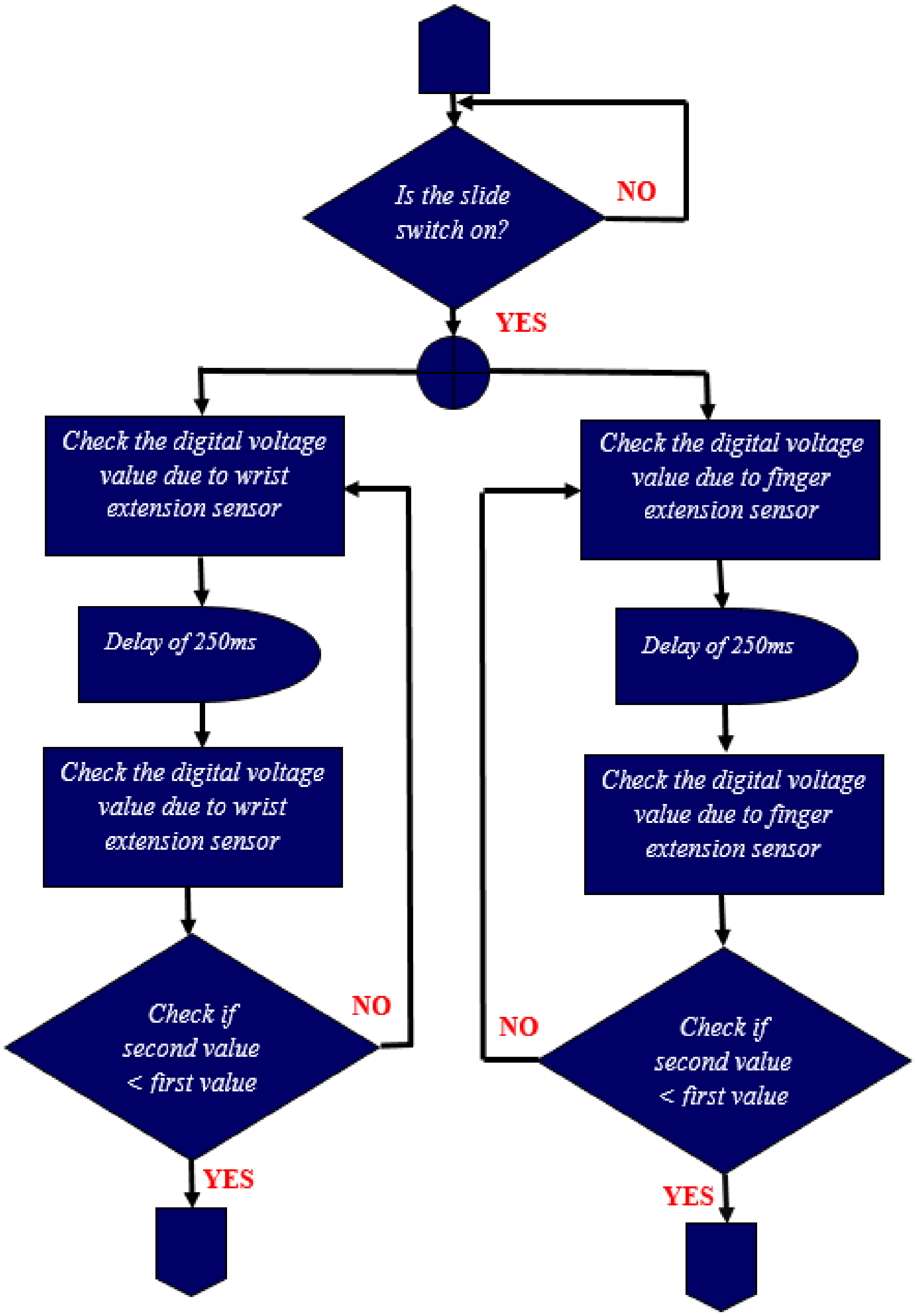


Figure 16. Process Flow of the Microcontroller Program to Detect Wrist and Finger Extensions (contd. 1)

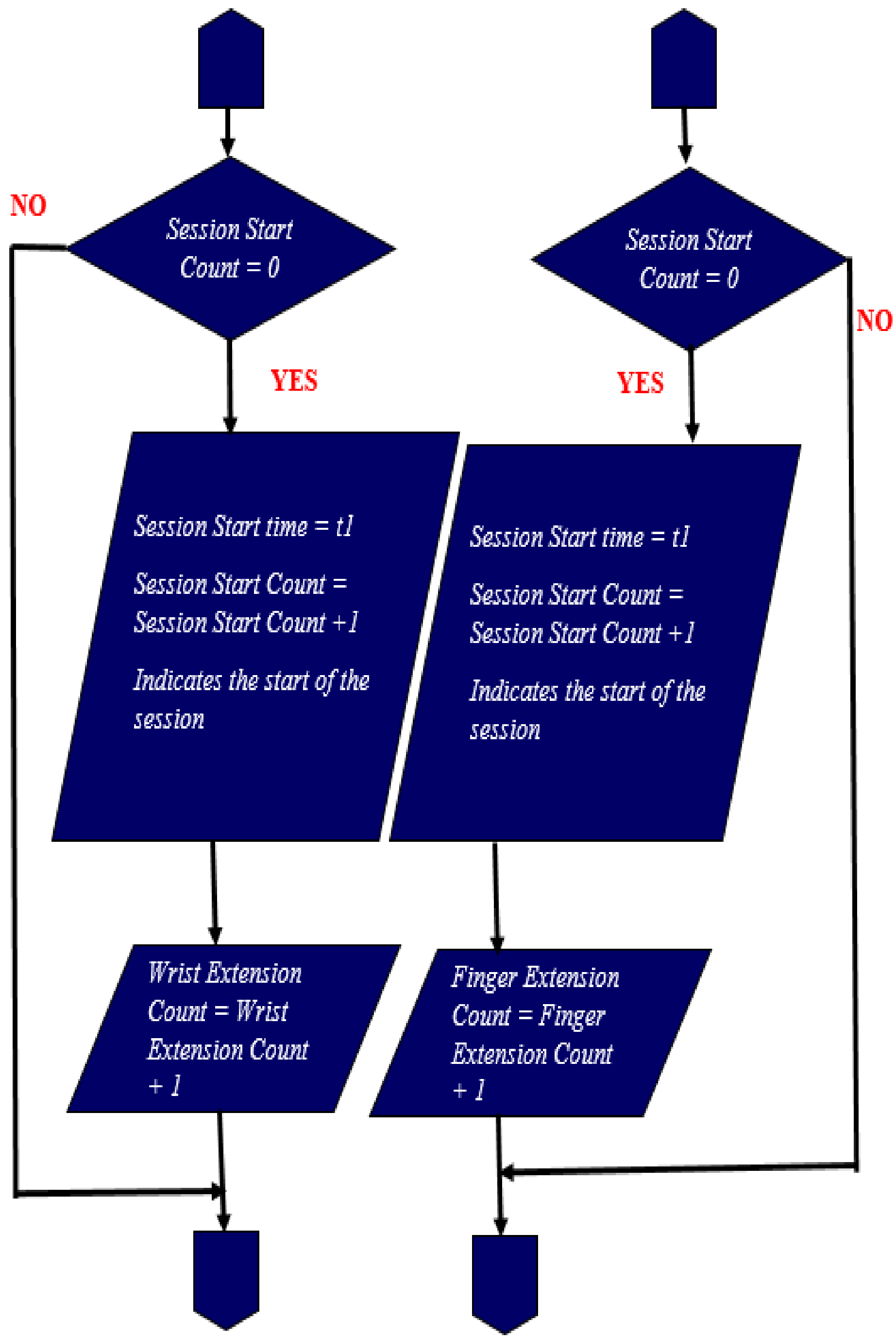


Figure 17. Process Flow of the Microcontroller Program to Detect Wrist and Finger Extensions (contd. 2)

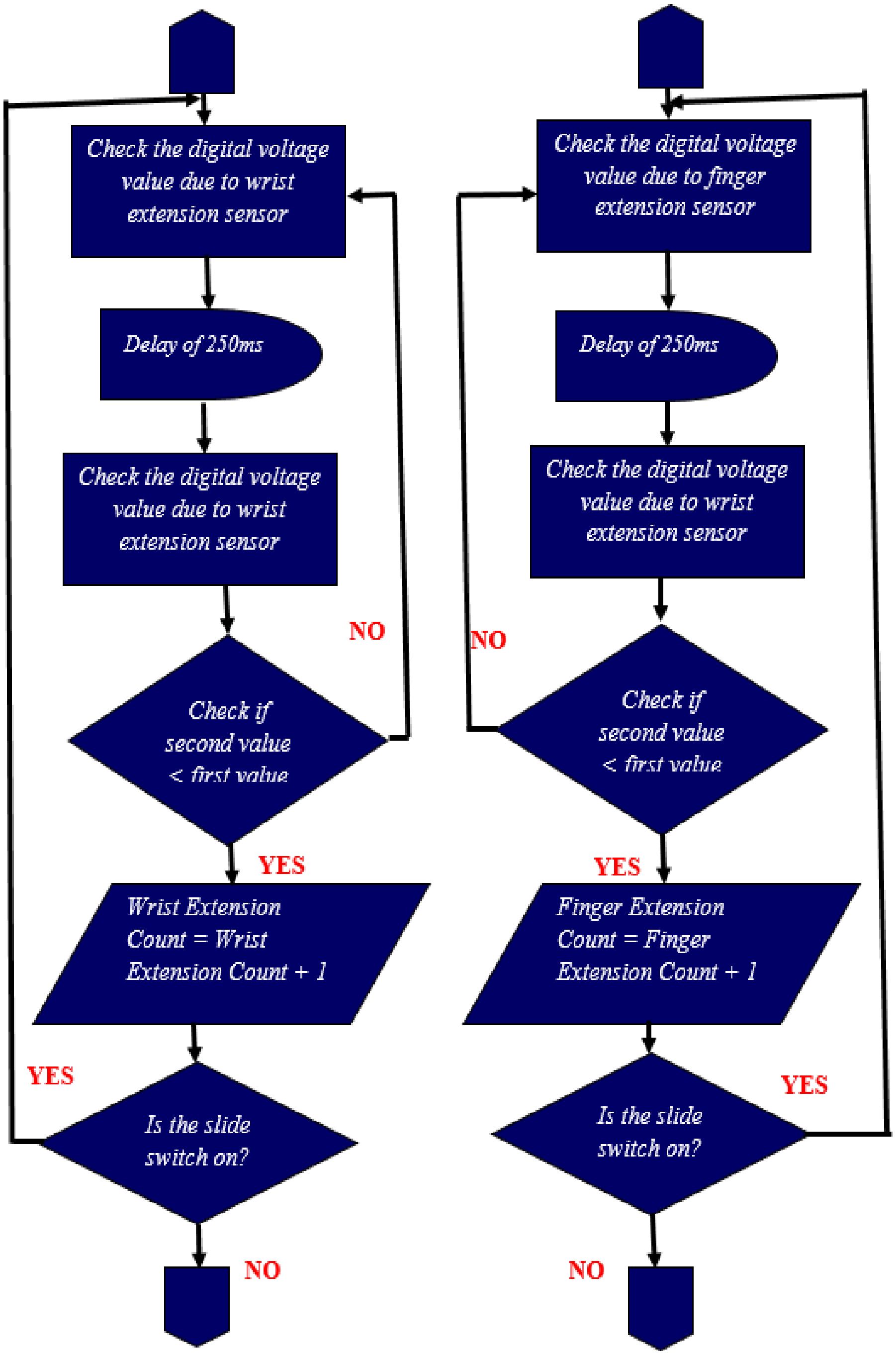


Figure 18. Process Flow of the Microcontroller Program to Detect Wrist and Finger Extensions (contd. 3)

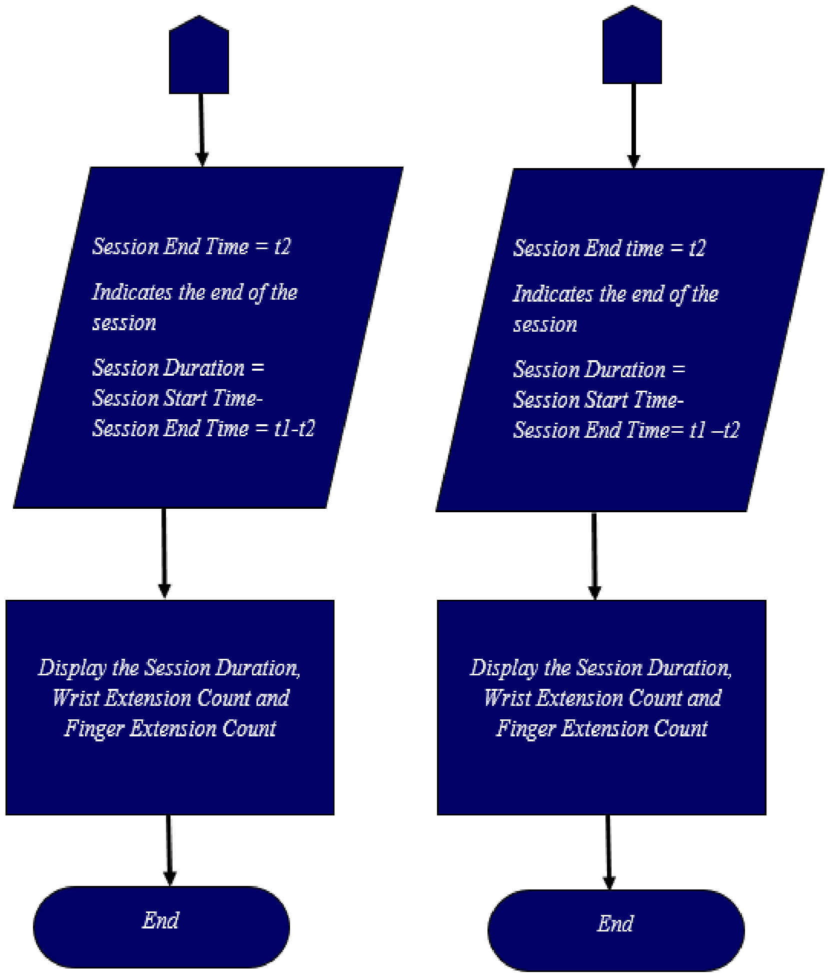


Figure 19. Process Flow of the Microcontroller Program to Detect Wrist and Finger Extensions (contd. 4)

The sensitivity of the sensor can be set within the program and the sensitivities for wrist and finger flexions can be adjusted for each patient.

Communication and Interfacing

Lightblue bean is equipped with LBM313 module. It is a low energy Bluetooth module and incorporates Bluetooth 4.0 communication protocol. The programming or display unit should be able to implement the Bluetooth 4.0 communication protocol and should have a MAC, Android or Windows operating system. This external device can be a mobile phone, tablet or laptop.

Display Unit

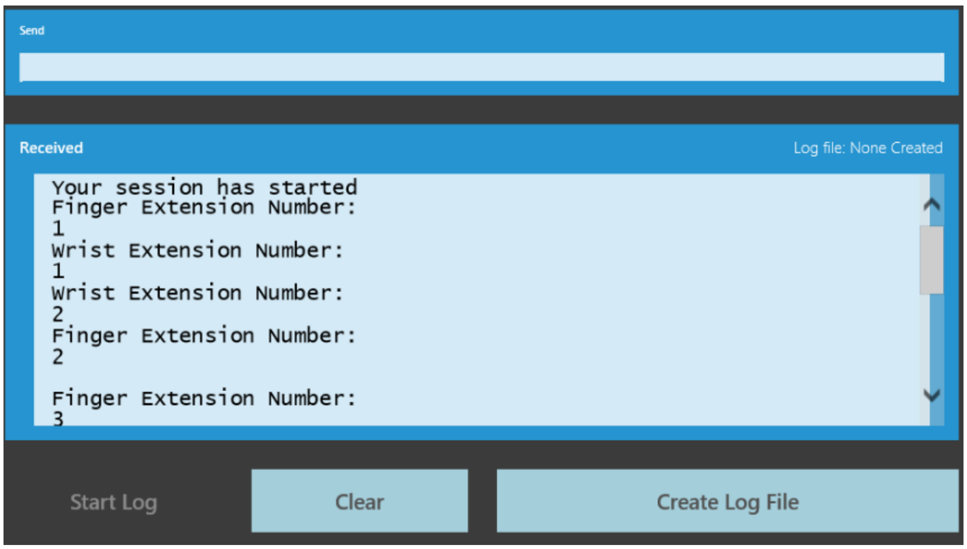
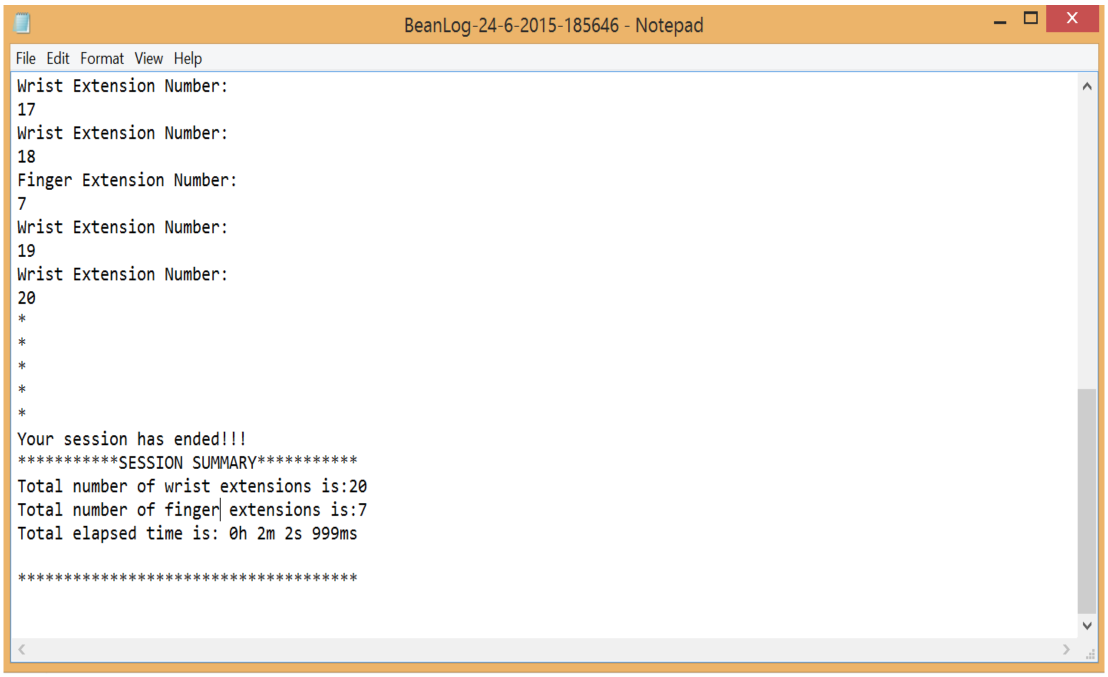


Figure 20. Serial Monitor of Beanloader Software Displaying the Extensions as and When They Are Detected

Whenever an extension is performed, it will be displayed on the laptop screen using the Beanloader software. This software has an inbuilt serial monitor that displays the outputs of the microcontroller program. The communication between this software and the bean is again via Bluetooth.

Reporting Module

The logs created in the Beanloader software using the serial monitor add-on can be exported as text files. At the end of the session, a report is generated that gives information about the number of wrist and finger extensions performed along with the time elapsed during the session. This text file can be used for future reference to monitor the patient's performance over a period of time.


BeanLog-24-6-2015-185646 - Notepad

File Edit Format View Help

```
Wrist Extension Number:
17
Wrist Extension Number:
18
Finger Extension Number:
7
Wrist Extension Number:
19
Wrist Extension Number:
20
*
*
*
*
*
Your session has ended!!!
***********SESSION SUMMARY***********
Total number of wrist extensions is:20
Total number of finger extensions is:7
Total elapsed time is: 0h 2m 2s 999ms

*************************************
```

Figure 21. Sample Log that is generated at the End of the Therapy Session

Overview of Integrated System

The individual modules are joined together to implement the complete system. Integrity in the design is ensured by verifying the continuity in connection between the modules. The data acquisition and conversion blocks are wired to the control unit and the control unit communicates with the display module via the Bluetooth communication protocol. The system is functional if it works only during the ON state of the slide switch and displays the count of wrist and finger extensions on the laptop screen as and when they are detected.

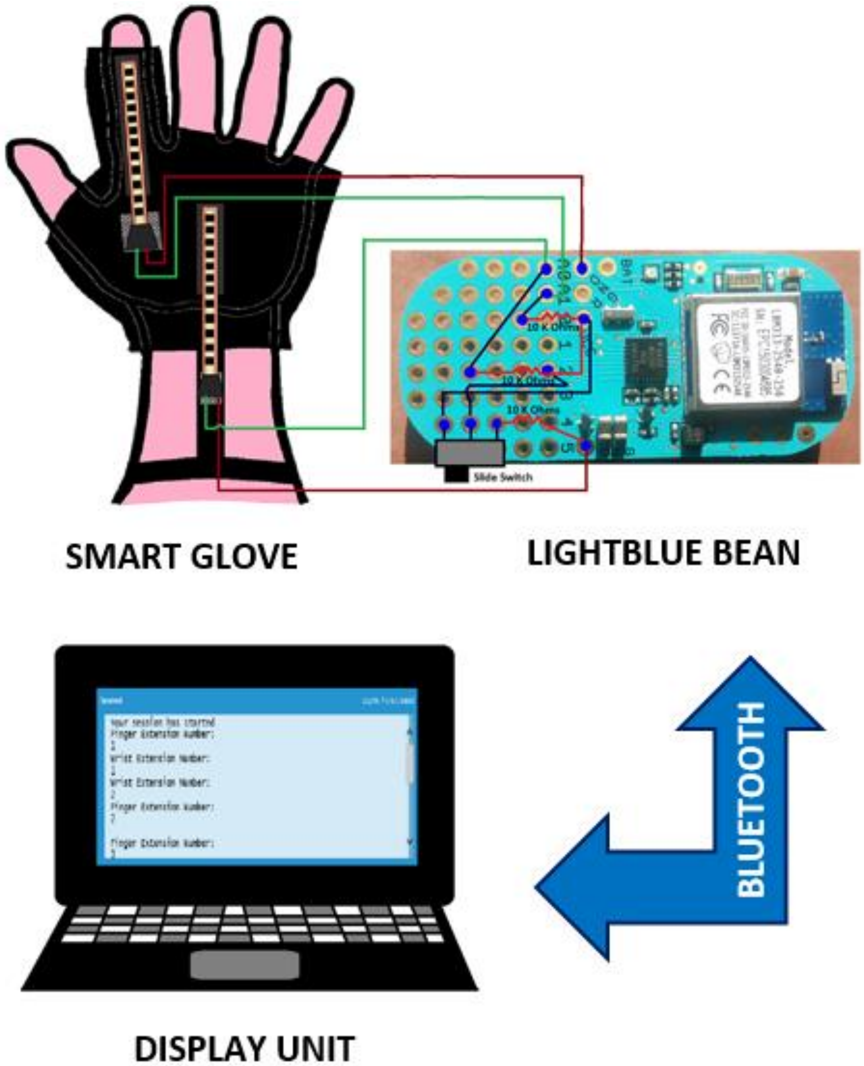


Figure 22. Integrated System for Smart Glove

When the switch is off, a session summary should be generated which can be exported as a text file. The system was functional from end to end and the effectiveness will be tested by implementing the glove in the stroke therapy sessions at the Swan Rehabilitation Clinic and Banner Good Samaritan Rehabilitation Out Patient Clinic in Phoenix.

CHAPTER 4

TESTING THE DEVICE

Bill of Materials

Table 1. Estimation of Total Fabrication Cost

Component	Number of Units	Cost/ Unit (dollars)	Total Cost of the Component (dollars)
Fingerless Cycle Glove (Size: XL)	1	.99	.99
Resistive Sensors	2	12.45	24.9
Lightblue bean	1	30	30
Solid Core Wire (22 AWG , 25 inches)	1	2.5	2.5
10 K Ohm Resistor	2	.25	.5
Slide Switch	1	.94	.94
Neoprene Fabric (58*60 inches)	1	4.89	4.89
Velcro Strips (.75 inches width)	1	1.5	1.5
Connector Pins(Male + Female)	2	.5	1
Slide Switch	1	.95	.95
Total Fabrication Cost (dollars)			68.24

Healthy Subject

The glove can be validated for its effectiveness by testing it on stroke patients with different levels of impairment: low, medium and high. Stroke patients usually have varying amounts of impairments in the left and right portions of the body. The amount of spasticity can even vary between wrist and fingers. Hence the glove should be able to capture the different types of extensions by varying the levels of sensitivity independently for each subject.

Before testing the Smart Glove on stroke patients, it was initially tested for its effectiveness while I performed three different tasks. The tasks were performed while wearing the glove and were carefully chosen to incorporate large number of finger and wrist extensions. This was ensured by performing the tasks repetitively.

The three tasks performed were: Picking up and dropping 50 coins in a piggy bank, pouring water from a 250 ml cup to a 450 ml bottle and the reverse, 30 times and opening an Altoid can and closing it, 30 times. In the microcontroller program, sensitivity levels are set from 0 to 100. Any number below 20 can be considered very sensitive. Sensitivity between 20 and 60 confirms to moderate levels and anything above 60 represents low sensitivity. For performing the above listed tasks, the sensitivity levels for wrist and finger extension were set at 40. Anything lesser than 40 was picking extensions that were not related to the task being performed. Even a slight jerk of the hand while performing the task was being counted as an extension. A value more than 40 was not able to capture the subtle extensions made while doing tasks like dropping the coin in the piggy bank and opening the Altoid can. Each session implemented the three tasks and a total of 3 sessions were recorded for averaging and comparing results.

Figure 23. Tasks Performed while Testing the Glove on Self

Table 2. Summary of the 3 Sessions of Testing on Healthy Subject

Session Number	Wrist Extensions	Finger Extensions	Total Extensions	Total Time (min)	Average Total Extensions	Average Total Time(min)
1	76	120	196	15.45	206	15.21
2	145	72	217	15.1		
3	116	91	207	15.07		

Average session duration was 15.21 minutes. The glove was able to capture the different types of extensions performed during the sessions.

Testing on Stroke Patients

The Smart Glove was tested on stroke patients at the Swan Rehabilitation Centre and Banner Good Samaritan Out Patient Clinic. The patients had different levels of impairment depending on the magnitude of stroke attack or traumatic brain injury. Hence for the testing process, a patient wise procedure is adopted and modifications to the design are implemented or suggested based on the feedback from successive sessions. Initially the patients had to wear the glove and perform few finger and wrist extensions. Because patients had varying degrees of motor impairment, the sensitivity levels were set to detect the maximum extension each could perform. The patients were instructed to perform a box and block task where they were seated at table and asked to pick up a block from the table and drop it into a box on the floor.

Figure 24. Stroke Patient Performing Box and Block Test during Rehabilitation Therapy

Table 3. Session Log for Patient No.1

Date of Session	6/23/2015
Gender	Female
Affected Limb	Left
Cause of Disability	Stroke Attack
Location	Swan Rehabilitation Clinic
Impairment Level	High
Sensitivity Levels	Wrist Extension: 30, Finger Extension: 20
Extensions Detected	Wrist Extensions: 17, Finger Extensions: 3
Total Session Time	8.78 minutes
Tasks Performed	1. Picking 5 wooden alphabet blocks from the table and putting them in a bucket 2. Picking 5 sponge blocks from the table, squeezing them and putting them in a bucket
Observations	The subject had difficulty wearing the glove as she was not able to open her hand to slide her fingers into the glove openings. Sometimes the therapist assisted the patient in extending fingers and wrist. Such passive movements cannot be distinguished from active movements by the glove. It recorded all the extensions irrespective of whether they were voluntary or forced. The finger extensions were mostly restricted to the distal regions of the fingers. Smart Glove is designed to detect the extensions in the proximal regions of the fingers. The subject was not able to perform the proximal extensions due to the nature of her disability. The multifiber wires soldered on the Arduino board were brittle. The subject could perform the task without making significant wrist extensions. This compensation was not noticed by the therapist but was detected by the glove. Thus the system can provide feedback to the therapist as to whether or not the patient is making the requested movements.
Changes made to the Design after the Session	The finger slots of the glove were cut expect for the slot for the index finger on which the sensor was mounted. Solder on the Lightblue bean was reinforced to strengthen the connections.

Table 4. Session Log for Patient No.2

Date of Session	6/24/2015
Gender	Male
Affected Limb	Left and Right
Cause of Disability	Traumatic Brain Injury
Location	Swan Rehabilitation Clinic
Impairment Level	Medium in left hand, Low in right hand
Sensitivity Levels	Wrist Extension: 15, Finger Extension: 20
Extensions Detected	Left hand-Wrist Extensions: 15, Finger Extensions: 3
	Right hand-Wrist Extensions: 7, Finger Extensions : 11
Total Session Time	Left hand: 2.05 minutes, Right hand: 1.92 minutes
Tasks Performed	Picking 10 sponge blocks from the table, squeezing them and putting them in a bucket
Observations	The tasks were performed in different ways in both the hands due to the different levels of impairment. The finger extensions were mostly restricted to the distal regions of the fingers and Smart Glove could pick up only the proximal extensions. The subject couldn't keep track of the type of extensions he performed during the task as he was looking away from his hands most of the time.
Changes made to the Design after the Session	Subjects were told when they were not making the requested movements.

Table 5. Session Log for Patient No.3

Date of Session	7/2/2015
Gender	Male
Affected Limb	Left
Cause of Disability	Stroke Attack
Location	Banner God Samaritan Out Patient Clinic
Impairment Level	Low
Sensitivity Levels	Wrist Extension: 15, Finger Extension: 20
Extensions Detected	Wrist Extensions: 64, Finger Extensions: 22
Total Session Time	5.68 minutes
Tasks Performed	Picking sponge balls from the table, squeezing them and putting them in a bucket till he felt tired
Observations	The glove was able to consistently detect extensions for the set sensitivity levels. There were no restrictions in hand movements after wearing the glove. The patient was carefully instructed to perform the task in a specific manner before the start of the session. This enhanced the number of repetitions of wrist and finger extensions recorded in the session. The therapist kept track of the session logs of the extensions detected by the glove that were populated in real time on the display monitor. Whenever compensation was noticed, the patient was informed. This enabled the patient to perform the task in the requested manner consistently.
Changes made to the Design after the Session	None

Table 6. Session Log for Patient No.4

Date of Session	7/2/2015
Gender	Male
Affected Limb	Left
Cause of Disability	Stroke Attack
Location	Banner Good Samaritan Out Patient Clinic
Impairment Level	Low
Sensitivity Levels	Wrist Extension: 15, Finger Extension: 20
Extensions Detected	Wrist Extensions: 14, Finger Extensions: 13
Total Session Time	2.32 minutes
Tasks Performed	Picking sponge balls from the table, squeezing them and putting them in a bucket till he felt tired
Observations	The glove was able to consistently detect extensions for the set sensitivity levels. There were no restrictions in hand movements after wearing the glove. The patient was carefully instructed to perform the task in a specific manner before the start of the session. This enhanced the number of repetitions of wrist and finger extensions recorded in the session. The therapist kept track of the session logs of the extensions detected by the glove that were populated in real time on the display monitor. Whenever compensation was noticed, the patient was informed. This enabled the patient to perform the task in the requested manner consistently.
Changes made to the Design after the Session	None

CHAPTER 5

RESULTS

Smart Glove was successfully fabricated and the total cost of fabrication was $68.24 making it potentially affordable for clinics and patients. Proper communication was established between the data acquisition, data conversion, data processing and display modules. Resistive sensors mounted on the Smart glove were able to detect finger and wrist extensions performed by both control subjects and stroke patients while performing therapy. The sensitivities for detecting wrist and finger extensions could be adjusted independently depending on the amounts of spasticity manifested in the wrist and fingers. Additional Velcro straps were stitched on the glove to provide a snug fit to the users.

Successful interfacing was established between the external hardware and control unit. Microcontroller was programmed to work according to an algorithm that checked the resistance values of the sensors every 250 ms. An extension was detected by the continuous decrease in the resistance of a sensor over a timeframe. The sensitivity values could be adjusted between 0 and 100 within the program. Duration of the therapy session can be expressed to the precision of milliseconds. The glove detected extensions only when the slide switch was ON.

The serial monitor in the bean loader software was able to populate the count of wrist and finger extensions whenever they were performed by the subject during the therapy sessions. At the end of the session, a summary was generated having the details of the total number of extensions performed along with the total duration of the session. The log in the serial monitor was also exported as a text file.

Before testing the glove on stroke patients, it was tested on myself to ensure proper functionality. A set of tasks that incorporated extensive wrist and finger extensions were performed and the session summary was collected for 3 sessions. The glove was able to detect the wrist and finger flexions performed for a sensitivity level of 40. The average session duration was 15.21 minutes and average number of extensions performed were 206. Even though the total number of extensions performed during the sessions were similar, large variation was observed in the number of wrist extensions and finger extensions performed for the same set of tasks between the sessions.

The glove was tested for its effectiveness on stroke patients who were instructed to wear the glove while performing the tasks during therapy sessions. Reviews and feedback were collected after every session and modifications to the glove design were made over the sessions to facilitate unrestricted hand movements of the subjects while performing therapy. The glove was able to detect the different types of extensions in stroke patients with various levels of impairments. This was achieved by carefully adjusting the sensitivity levels for wrist and finger extensions based on the amount of impairment. By consistently making changes to the design over successive sessions based on the feedback collected, the subjects were able to make wise use of the glove in their sessions. The first prototype of Smart Glove was functionally effective.

Summary of Findings

1. The glove can detect wrist and proximal finger extensions in stroke and TBI patients.

2. The glove could not distinguish between active and passive movements.

3. It could not detect distal finger extensions which are more prevalent than proximal extensions in lower functioning patients.

4. The glove could detect when patients were not performing the task as requested by the therapist.

5. The battery life of the glove was limited to 30 minutes.

6. The connections to the Arduino were not reliable and easily broken.

CHAPTER 6

DISCUSSION

Several changes were made to the glove during testing and included removing all finger sleeves except the index finger and shortening of leads to the Arduino. While this first prototype was functionally effective, the glove requires extensive modifications before it can be extensively tested in the clinic and at home.

Initially when the glove was tested for its functionality on myself, there was a huge difference in the number of wrist and finger extensions performed across the sessions for the same set of tasks. This could be because of the different ways by which a task can be completed. While performing the task in the session, much attention is not given to the type of movements incorporated in the task. Stroke rehabilitation therapy sessions are usually evaluated by the number of times a task is completed. Smart Glove can give critical information about the type of movements incorporated to complete an activity. This scenario was also observed in Patient 2 at the Swan Rehabilitation Centre. As both his hands had different levels of spasticity, there was significant difference in the number of finger and wrist extensions detected while performing the same task using different hands. Desired incidence of particular types of extensions while doing a task could be achieved by giving proper instructions and feedback to the subject during the task. This was verified in Patient 3 and Patient 4 as they performed more number of wrist and finger extensions during the sessions. They were given clear instructions on how to perform the task before the session. Further the therapist could identify compensation with the help of the session logs generated in real time on the display monitor. Whenever compensation was noticed, the patients were informed. This helped them in performing the requested movements consistently.

Patient 1 had extreme difficulty in wearing the glove as she had high levels of spasticity in her hands. She was not able to extend her fingers to slide them into the respective finger slots of the glove. After this session, the finger slots of the glove were cut except the slot for the index finger on which the sensor was mounted. In the successive sessions, the subjects didn’t have enhanced difficulty in wearing the glove. Also, the therapist assisted her in performing few extensions at times. The glove was not able to detect the active and passive extensions. This problem could be solved by pausing the system if and when the therapist desires to make passive movements. This may also encourage the therapists to avoid making passive movements.

The laptop screen interface was not effective in providing feedback to the patient and should be redesigned. They were not able to focus on the serial monitor to get a feedback on the type of extensions detected. This could be solved by providing auditory feedback when the movements are being performed correctly. This avoids the need to provide additional attention to read values populated on a computer screen while performing a task. Through the auditory feedback the patients can alter their way of doing a task to increase the incidence of a particular type of extension.

Most of the patients could perform only distal extensions of the fingers. The glove was designed to detect proximal extensions.

After the session with patient 1, it was also observed that the wire connections on the Lightblue bean were brittle. This was mainly because multifiber conduction wires were used to solder the connections on the perf board attached to the bean. This issue could be solved by replacing the multifiber wires with thin solid core copper conduction wires. As a temporary remedy, the solder connections on the perf board were reinforced.

One further potential benefit of the glove may be to avoid use-dependent spasticity. Spasticity is a muscle function disorder characterized by stiffness in the muscles which limits flexible joint movements. Affected patients lack the ability to control muscle movements due to loss of corticospinal signals to the spinal cord. Spasticity is observed in 30% of the stroke patients and happens in the initial few days or weeks after stroke attack (Mayer and Esquenazi 2003). Wissel et al. (2010) conducted a study among 103 stroke patients to observe the different forms of spasticity (Wissel et al. 2010). In the upper extremity, spasticity primarily affects elbow (79% of patients) and wrist (66%). The most common form of spasticity is the flexion of elbow, wrist and fingers (Casals et al. 2011). Because spasticity can be induced through intensive movement such as that occurring during rehabilitation, it is one of the major obstacles in delivering motor rehabilitation. The Smart Glove could be used to avoid such use-dependent spasticity by determining the amount of wrist/finger extension that induces spasticity and allowing the therapists to avoid such movements.

Our results show that the Smart Glove can detect wrist and proximal finger extension in patients with varying degrees of impairment. Several design flaws will need to be overcome before it can be tested in a larger population of patients both in the clinic and at home. However, the Smart Glove has the potential to be a low-priced assistive device that can enhance the motor recovery after stroke or brain injury.

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