Some Investigations in Brain-Machine Interface based Robotic Manipulation

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IN

MECHANICAL ENGINEERING
BY

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DECLARATION

I declare that the research work reported in the thesis entitled "Some Investigations in Brain-Machine Interface based Robotic Manipulation" for the award of degree of Doctoral of Philosophy in Mechanical Engineering has been carried out by me under the supervision of Prof. DS Nagesh, Department of Mechanical Engineering, Delhi Technological University, India. The research work embodied in this thesis, except where otherwise indicated, is my original research. This thesis has not been submitted by me in part or full to any other University for the award of any degree or diploma. This thesis does not contain other person's data, graphs or other information, unless specifically acknowledged.

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CERTIFICATE

This is to certify that the Ph.D. thesis entitled "Some Investigations in Brain-Machine Interface based Robotic Manipulation" submitted to Delhi Technological University, New Delhi, for the award of Doctoral of Philosophy in Mechanical Engineering, is based on original research work carried out by me, under the supervision of Prof. DS Nagesh, Department of Mechanical Engineering, Delhi Technological University, Delhi, India. It is further certified that the work embodied in this thesis has neither partially nor fully submitted to any other university or institution for the award of any degree or diploma.

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Rizwan Jafar

Mohd Rizwan Jafar

Dedication

This thesis is dedicated to my little daughter ‘Batool Sayyada.’You have made me stronger, better, and more fulfilled than I could have ever imagined.

I have dedicated this to you as a symbol of hard work and dedication and to show that you can do what you love, be great at what you do, and achieve any and all dreams if you trust in the Lord, who has perfectly prepared your steps.

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Abbreviations

ANN	Artificial Neural Network
BCI	Brain Computer Interface
BMI	Brain Machine Interface
CL	Central Line
DWT	Discrete Wavelet Transformation
EEG	Electro-encephalographic
EMG	Electro-myographic
EOG	Electro-oculographic
IoT	Internet of things
KNB	Kernel Naive Bayes
KNN	K-Nearest Algorithm
LCL	Lower control limit
LDA	Linear Discriminant Analysis
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RMS	Recorder and medicare systems pvt ltd
SCI	spinal cord injury
SHD	Self-Help Device
SLR	Systematic Literature Review
SPC	Statistical Process Control
SQC	Statistical quality control
SVM	Support Vector Machine
UCL	Upper control limit

Nomenclature

M_d	Molar Flux from diffusion
M_e	Molar flux from the electrophoretic effect
μ	Ion mobility in the medium
C	Concentration of a specific ion

D	Diffusivity
X	Distance across the membrane
Ψ	Local potential
M_{K^+}	Molar flux of K^+ ions
I_{k+}	Current generated by K^+ ions
Z	valence of ions of interest
F	Faraday's Constant
R	Gas Constant
T	Absolute temperature

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Figure 32: Scanning electron microscope image of Al powder after milling for a) 1 hour, b) 2 hour, c) 4 hour, d) 8 hour

Figure 33: Scanning electron microscope image of nanocomposite after milling for (a) 1 hour, (b) 2 hours, (c) 4 hours, and (d) 8 hours.

Chapter 1

INTRODUCTION

1.1 Mechanism of generation of action potential in the brain:

To comprehend BMI (Brain-Machine Interface) fully, it is essential to first have a clear understanding of the human brain. The brain is a vast network of interconnected neurons and supporting cells, with neurons constantly communicating with each other through electrical pulses referred to as action potentials. Each neuron has three main parts: dendrites, soma, and axon. Dendrites, which are hair-like structures, receive information from the environment and transfer it to the soma, where the information is processed. The axon sends information out of the neuron and is attached to the soma. Neurons come in various shapes and sizes, and their distribution throughout the nervous system is determined by their specific functions. For example, neurons in the mesencephalic nucleus of the cranial nerve only have a cell body, while neurons in the cerebral Purkinje cells have the most significant number of dendrites.

The place where two neurons are connected is called a synapse. Based on the location of neurons, whether before or after a synapse, we can classify them as presynaptic and postsynaptic neurons, respectively. Whenever a piece of input information is received from a presynaptic neuron, the firing rate of postsynaptic neurons changes. A piece of excitatory information increases the frequency of firing of the action potential, while a piece of inhibitory information decreases the frequency of firing of the action potential[2]. Amplitude remains the same. The pathways for the flow of information are also different for different stimuli. Hence This increase and decrease in action potential, along with the different pathways, contribute to the generation of different waveforms of electrical potential for different kinds of stimuli inside the nervous system [3][4][5]. If we can differentiate between these changes in the waveforms, we can use them to generate control signals for operating machines.

It is intriguing to note that each neuron in the human nervous system continually generates action potentials, with an estimated total of more than 100 billion neurons in the human brain. This means that a massive amount of electricity is generated in our brains every second, through a passive mechanism involving the diffusion of ions. In the following sections, we will delve further into the process of generating action potentials.

The inside environment of a neuron is separated from its outside environment with the help of a neural membrane. This neural membrane prevents the interaction of the ions inside the cell with the ions outside the cell. The interaction can only occur with the help of ion channels and ion transporters. The environment inside the cell is generally more negative than the outside environment. For an average neuron, the difference between the outside and inside is about -65 mV. It is known as resting membrane potential.

Nothing happens inside and outside the cell when there is no concentration gradient. However, when there is a concentration gradient, the flow of ions starts.

If the membrane is selectively permeable to K^+ ions, K^+ ions will move outside of the cell over time because there is less concentration outside. As positive ions move outside the cell, the inside voltage will drop, and the outside voltage will increase. The negative ions used to balance positive ions will remain uncoupled inside the cell. At the same time, the positive ions which come outside will create a net positive charge outside. The diffusion will continue to happen until a resting membrane potential is reached.

Over time, K^+ ions that went outside would want to come in as they are attracted to the negative uncoupled ions inside, and the k^+ ions inside would continue to diffuse out due to the concentration gradient; when there is a balance between these two, the resting membrane potential reaches. The resting membrane potential in mammals for K+ is about -65 mV, while for Na+ is around +20 mV. If there is any change in the concentration gradient, there will also be a change in the resting membrane potential.

The resting membrane can be derived mathematically also[6][2]

Let

M_d= Molar Flux from diffusion

M_e= Molar flux from the electrophoretic effect

μ= Ion mobility in the medium

C= Concentration of a specific ion

D=Diffusivity

x= Distance across the membrane

Ψ= Local potential

M_{K^+}= Molar flux of K^+ions

I_{k+}= Current generated by K^+ions

z= valence of ions of interest

f= Faraday's Constant

R= Gas Constant

T= Absolute temperature

Molar flux from diffusion

$M_d = -D\frac{dc}{dx}$ ……. eq. 1

Molar flux from the electrophoretic effect

$M_e = -\mu C\frac{d\Psi}{dx}$ ……. eq. 2

Total Flux

$M_{k+} = M_d + M_e$

$= -D\frac{dc}{dx} - \mu C\frac{d\Psi}{dx}$ …… eq. 3

We are more interested in the Current and the molar flux, so let's relate this molar flux to the current.

$I_{k+} = M_{k+}zf = -zf(D\frac{dc}{dx} + \mu C\frac{d\Psi}{dx})$ ……….. eq. 4

According to Einstein's relationship

$\mu = \frac{zDf}{RT}$ ……….. eq. 5

Putting the value of μ from eq.5 in eq 4

$I_{k+} = -zfD(\frac{dc}{dx} + \frac{zfC}{RT}\frac{d\Psi}{dx})$

At equilibrium i.e at resting membrane potential total current is zero

$-zfD(\frac{dc}{dx} + \frac{zfC}{RT}\frac{d\Psi}{dx}) = 0$

$\frac{d\Psi}{dx} = \frac{-RT}{zf}.\frac{1}{c}.\frac{dc}{dx}$

Integrating the equation between inside and outside conditions

$$\int_{Inside}^{Outside} \frac{d\Psi}{dx} = \int_{Inside}^{Outside} \frac{-RT}{zf} \cdot \frac{1}{c} \cdot \frac{dc}{dx}$$

$$\Psi_{outside} - \Psi_{inside} = \frac{-RT}{zf} ln \frac{K^{+}_{Inside}}{K^{+}_{Outside}}$$

$$V_{m} = \frac{RT}{zf} ln \frac{K^{+}_{Outside}}{K^{+}_{Inside}}$$

$$V_{m} = \frac{58}{z} log \frac{K^{+}_{Outside}}{K^{+}_{Inside}}$$ ……. Eq 6

The above equation is valid for other ions too. If we put the measured values of, K^{+}we will get a resting potential of about -65mV once the resting potential. If we switch the permeability of the neural membrane from sodium to potassium, we will get a resting potential of about +20 mV for sodium. Once the resting potential of sodium has reached, changing the permeability again to potassium will bring the resting potential back to - 65 mV. This change of potential from -65 mV to +20 mV and back to -65 mV is called an action potential.

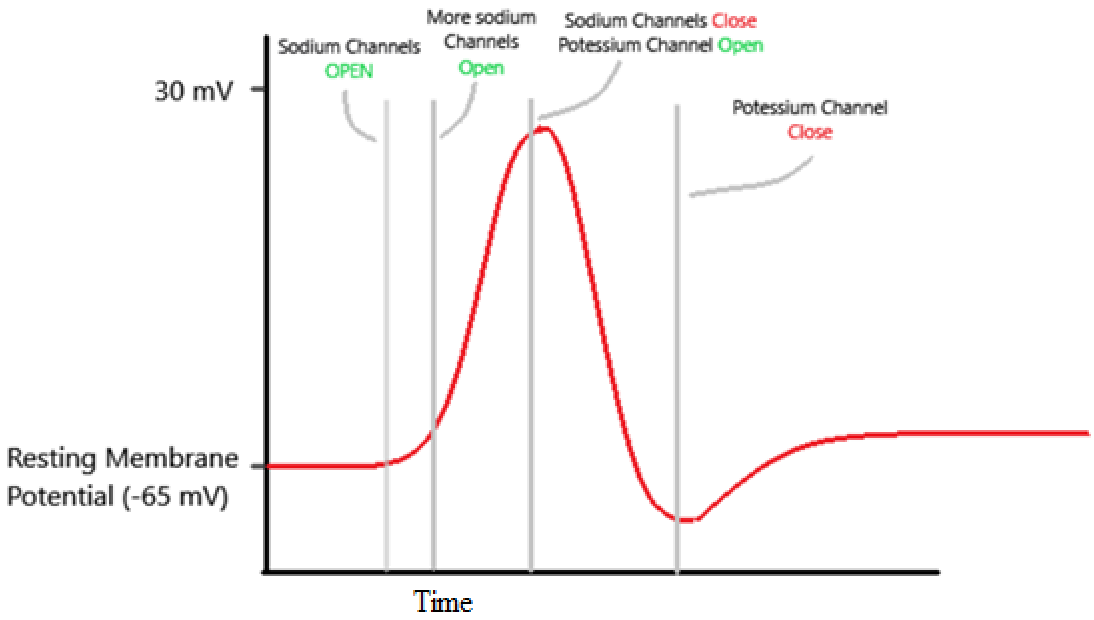


Figure 1: Representation of different phases of action potential[3]

The combined action potential of a nerve or a group of nerves is responsible for the actuation and control of sensory as well as motor functions of different parts of the human body.

1.2 Need for the present work

The motivation behind this dissertation is rooted in the field of spinal cord injury (SCI). The human spinal cord is divided into 31 segments, each of which is responsible for controlling different parts of the body. An injury to any segment can block the pathway, leading to loss of voluntary control of various body parts depending on the location of the injury. One such severe form of disability is quadriplegia, where all limb functions are lost. Every year, an average of 500,000 new cases of spinal cord injury are reported worldwide[7]. Rehabilitation for quadriplegia is extremely challenging and often leads to partial or total dependence on caregivers. This dependence on others can pose a significant challenge, especially for patients from nuclear families.

To address this challenge, the development of self-help devices (SHD) can prove to be extremely beneficial. These devices can provide partial or total freedom to patients, giving caregivers the peace of mind to attend to other responsibilities, such as work or shopping, knowing that their loved ones have the ability to take care of some of their needs independently. However, the development of SHDs for quadriplegic individuals is a challenging task. The injury, which is typically located in the upper region of the cervical spinal cord, often leads to paralysis of all limbs and speech impairment, making it difficult to obtain control signals for the SHD[8][9][10]. Brain-Machine Interfaces (BMI) provide a solution by allowing us to obtain control signals from these severely disabled individuals to operate the SHD.

BMI-based self-help devices provide a new and innovative solution to the rehabilitation of quadriplegia. These devices use electrodes implanted in the central or peripheral nervous system or placed externally on the scalp to monitor brain activity and translate it into control signals for a rehabilitation device. This enables individuals with quadriplegia to regain some level of independence and control over their limbs. The use of BMI technology in rehabilitation offers numerous benefits, including improved mobility, increased independence, and enhanced quality of life.

The aim of this thesis is to examine the development and implementation of BMI-based self-help devices for the rehabilitation of quadriplegia. The focus will be on the design and development of these devices, the technology used, and the benefits and limitations of their use. The thesis will also explore the various clinical trials and studies that have been conducted to evaluate the effectiveness of these devices in the rehabilitation of quadriplegia.

The use of BMI-based self-help devices is a rapidly evolving field, and there is a significant amount of research and development being conducted in this area. The objective of this thesis is to provide a comprehensive overview of the current state of the art in this field and to identify the key challenges and opportunities that lie ahead. This will be achieved through a thorough review of the existing literature, and by conducting original research to explore the use of these devices in rehabilitation.

Chapter 2

LITERATURE REVIEW

The primary objective of self-help devices is to enhance the capabilities of individuals with disabilities, enabling them to perform daily tasks and interact with their surroundings more efficiently. Selecting the right technology and features for a self-help device is crucial in ensuring its effectiveness and user acceptance.

Currently, there are several technologies available for developing self-help devices, including EEG-based brain-computer interfaces, Electromyography devices, speech recognition-based devices, eye-tracking-based devices, and more. Each of these technologies comes with its own set of advantages and limitations that can impact the usefulness and acceptability of the device.

Despite the availability of technically advanced self-help devices, it has been observed that the rejection rate of these devices is still quite high. This highlights the need for further research and analysis of the existing assistive devices in the literature. It is crucial to understand the issues and barriers associated with these devices and to identify areas for improvement.

To delve deeper into this topic, we conducted a thorough literature review aimed at discovering the current state-of-the-art in the design of self-help devices for individuals with quadriplegia, identifying the functional and non-functional requirements for these devices, and exploring any barriers that may hinder the development and implementation of these devices.

2.1 Methodology for the Review:

We conducted the review by following the Systematic Literature Review (SLR) methodology. The review was done as per the PRISMA guidelines. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)[116] is a set of guidelines for reporting systematic reviews and meta-analyses.

In order to get the targeted results, the expert boolean search was conducted in multiple databases using the following query- ("Self-help devices" OR "Assistive Devices" OR "Assistive Product" OR Assistive Technology) AND "Quadriplegia." Only original articles, technical and case studies, conference articles, and literature reviews published on Science Direct, Pubmed, IEEE Xplore digital library, and Web of Science between 2014 to 2021 were taken into consideration for this study. After discarding the duplicates, articles were screened based on their title and abstracts. Articles unrelated to SHD development or about the patients who require mechanical ventilation or where the upper limb is functional were discarded. Initially, 222 total articles were found, but after the exclusion of articles using the above-mentioned criterion, 77 articles were used for further review.

The articles were categorized based on the type of control signals. After that, a detailed review was done. Table 1 shows the results obtained from the literature review. The discussion about them is available in the sections following the table.

Table 1: Descriptive analysis of studies included in the present literature review

Title	Author	Year	Type	Type of Signal Used	Purpose
Development of a system of aid for use the computer through a wireless system for people with quadriplegia in Ecuador	(Tello-Morales, Pinos-Velez and Serpa-Andrade [11]	2018	Experimental Study	Head, Neck and Shoulders movements	To design and implement prototype wireless that will allow the interaction between a person with quadriplegia and the computer, through the control of your head, neck, and shoulders.
Self-Help Devices for Quadriplegic Population: A Systematic Literature Review	Orejuela-Zapata, Rodriguez and Ramirez [12]	2019	Review	--	To find primary needs, expectations, and barriers of people with quadriplegia and caregivers

Electrooculography Based iOS Controller for Individuals with Quadriplegia or Neurodegenerative Disease	O'Bard *et al.*[13]	2017	Experimental Study	Electro Oculography Signals	To Use eye movements to create communication capabilities are testing through the administration of a typing test to measure characters typed per minute
Facial Position and Expression-Based Human–Computer Interface for Persons With Tetraplegia	Bian *et al.* [14]	2015	Experimental Study	Facial Position And Expression & Rgb Camera	To use nose position along with the mouth status (close/open) to control and navigate the cursor as computer user input
Variability Analysis on Gestures for People With Quadriplegia	Jiang, Duerstock and Wachs [15]	2018	Experimental Study	Gesture-Based Interface	To Use a gesture based interface to operate a game called PAC-MAN

Designing a Cost Effective Prototype of an Automated Wheelchair Based on EOG (Electrooculography)	Mubtasim Rafid Chowdhury *et al.*[16]	2018	Experimental Study	Electrooculography (Eog) Signal.	To Design an automated wheelchair to be operated by eye movements
Assessment of the Tongue-Drive System Using a Computer, a Smartphone, and a Powered-Wheelchair by People With Tetraplegia	Kim *et al.*[17]	2015	Experimental Study	Tongue Movements (Magnetic Tongue Stud)	To control computers, wheelchairs, and smartphones using voluntary tongue motion
GOM-Face: GKP, EOG, and EMG-Based Multimodal Interface With Application to Humanoid Robot Control	Nam *et al.*[18]	2014	Experimental Study	1)Tongue Movement; 2) Electrooculogram (Eog);3)Teeth	To communicate with the robot by selecting from a pre-defined menu using eye, tongue movements and teeth clenching

				Clenching Emg	
Simplistic Approach to Design a Prototype of an Automated Wheelchair Based on Electrooculography	M R Chowdhury *et al.*[19]	2018	Experimental Study	EOG	To develop a prototype of an automated wheelchair which can be controlled by directional movement of the eye using electrooculography (EOG) signal
Movement intention detection using neural network for quadriplegic assistive machine	Izzuddin *et al.*[20]	2015	Experimental Study	EEG Signal	To Use EEG signals to operate a wheelchair
Error-Free Text Typing Performance of an Inductive Intra-Oral Tongue Computer Interface for Severely Disabled Individuals	L N S Andreasen Struijk *et al* [21]	2017	Experimental Study	Tongue Movements	To use tongue movements for error free typing in a generally available text editing system

An EOG-Based Human–Machine Interface to Control a Smart Home Environment for Patients With Severe Spinal Cord Injuries	Zhang *et al.* [22]	2018	Experimental Study	Eye Blinking	To develop asynchronous EOG-based human machine interface (HMI) for smart home environmental control with the purpose of providing daily assistance for severe spinal cord injury (SCI) patients
Upper Body-Based Power Wheelchair Control Interface for Individuals With Tetraplegia	Thorp *et al.* [23]	2015	Experimental Study	Residual Shoulder Motion	To develop a body-machine interface (BMI) that leverages the flexibility and customizability of redundant control by using high dimensional changes in shoulder kinematics to generate proportional controls commands for a power wheelchair
Semi-Autonomous Tongue Control of an Assistive Robotic Arm for Individuals with Quadriplegia.	Hildebrand *et al.* [24]	2019	Pilot Study	Tongue Movements	To perform a pilot study to investigate whether semi-automation might further improve the efficiency of the intraoral tongue control interface when controlling an ARM.

AMiCUS-A Head Motion-Based Interface for Control of an Assistive Robot.	Rudigkeit and Gebhard [25]	2019	Experimental Study	Head Motions	To develop a Human-Robot Interface that enables tetraplegics to control a multi-degree of a freedom robot arm in real-time using solely head motion
A system for bedside assistance that integrates a robotic bed and a mobile manipulator.	A. Kapusta, et al [26]	2019	Experimental Study	Person's Pose Estimation	To develop a robotic system for bedside assistance that consists of a robotic bed and a mobile manipulator (i.e., a wheeled robot with arms which is controlled by person's pose using a pressure sensing mat.
A Stand-Alone Intraoral Tongue-Controlled Computer Interface for People With Tetraplegia.	Kong *et al.*[27]	2019	Experimental Study	Tongue Movements	To use embedded wireless tongue-operated assistive technology developed for people with tetraplegia to provide them a higher level of independence in performing daily living

					tasks, such as accessing computers, smartphones, and driving wheelchairs
Head Motion and Head Gesture-Based Robot Control: A Usability Study	Jackowski, Gebhard and Thietje [28]	2018	Usability Study	Head Motion And Head Gestures	To control a six degrees of freedom robot arm with gripper is controlled with head motion and head gestures only
A conceptual framework for designing Ambient assisted living services for individuals with disabilities in Uganda and South Africa	Kyazze, Wesson and Naudé [29]	2019	Review	--	To know main needs, expectations, and barriers of people with quadriplegia and caregivers
Beyond the gaze: Communicating in chronic locked-in syndrome.	Lugo *et al.* [30]	2015	Survey	--	To study Methods for communication with Locked in syndrome patients

Assessment of brain-machine interfaces from the perspective of people with paralysis.	Blabe *et al* [31]	2015	Survey	--	To Survey about user preferences for electroencephalography, electrocorticography, intracortical microelectrode arrays, as well as a commercially available eye tracking system
Safety and efficacy of medically performed tongue piercing in people with tetraplegia for use with tongue-operated assistive technology.	Laumann *et al.* [32]	2015	Experimental Study	--	To develop and test a medically supervised tongue-piercing protocol and the wearing of a magnet-containing tongue barbell for use with the Tongue Drive System (TDS) in persons with tetraplegia.
Exploring the experience of clients with tetraplegia utilizing assistive technology for computer access.	Folan *et al.* [33]	2015	Qualitative Study	--	To Understand of the experiences of clients with tetraplegia trailing assistive technologies for computer access

Development and functional demonstration of a wireless intraoral inductive tongue computer interface for severely disabled persons.	N S Andreasen Struijk *et al.* [34]	2017	Experimental Study	Inductive Tongue Computer Interface	To implement an alternative computer interface, which was fully embedded into the oral cavity and which provided multiple control commands for typing in computer.
Wireless intraoral tongue control of an assistive robotic arm for individuals with tetraplegia.	Lotte N S Andreasen Struijk *et al.* [35]	2017	Experimental Study	Tongue Movements	To fully control an assistive robotic arm using a wireless intraoral tongue interface.
Augmentative and Alternative Communication Effects on Quality of Life in Patients with Locked-in Syndrome and Their Caregivers.	Corallo *et al.* [36]	2017	Survey	--	To survey about quality of life in locked in syndrome disease
Associations between time since onset of injury and participation in Dutch people with long-term spinal cord injury.	de Ruijter *et al.* [37]	2018	Multicentre Cross-Sectional Study	--	To describe relationships between time since injury (TSI) and

					participation in individuals with tetraplegia and paraplegia
Qualitative assessment of tongue drive system by people with high-level spinal cord injury.	Kim *et al.* [38]	2014	Qualitative Study	--	To perform qualitative assessment of tongue drive system
A clinical screening protocol for the RSVP Keyboard brain-computer interface	Fried-Oken *et al.* [39]	2015	Qualitative Study	--	To propose a screening protocol that identifies requisite sensory, motor, cognitive and communication skills for people with locked-in syndrome to use brain-computer interface
Virtual typing by people with tetraplegia using a self-calibrating intracortical brain-computer interface.	Jarosiewicz *et al.* [40]	2015	Experimental Study	Intracortical Bci	To Use EEG Signals to Type in Custom made software

Voice-Activated Lightweight Reacher to Assist with Upper Extremity Movement Limitations: A Case Study.	Khalid *et al.*[41]	2015	Case Study	Voice Instructions	To design a functional and user-friendly reacher arm controlled by voice instructions for people with spinal cord injuries (SCIs). . Comparison study with healthy participants and an SCI participant was also done.
Time and Effort Required by Persons with Spinal Cord Injury to Learn to Use a Powered Exoskeleton for Assisted Walking	Kozlowski, Bryce and Dijkers[42]	2015	Qualitative Study	--	To quantify the time and effort required by persons with SCI to learn to use an exoskeleton for assisted walking
Speaking Ability while Using an Inductive Tongue-Computer Interface for Individuals with Tetraplegia: Talking and	Struijk LNSA, Benstsen B,	2018	Case Satudy	--	To study ability of speaking while using an inductive tongue-computer interface

Driving a Powered Wheelchair - a Case Study.	Gaihede M [43]				
Fully Implanted Brain-Computer Interface in a Locked-In Patient with ALS	Vansteensel *et al* [44]	2017	Experimental Study	Invasive Electrodes On Motor Cortex	To describe a method for communication in a patient with late stage amyotrophic lateral sclerosis (ALS), involving a fully implanted brain–computer interface that consists of subdural electrodes placed over the motor cortex
A vibrotactile p300-based brain-computer interface for consciousness detection and communication.	Lugo *et al.* [45]	2014	Experimental Study	Eeg (Elicit Event-Related Potentials)	To determine whether patients with locked-in syndrome (LIS) could elicit a P300 wave, using a vibrotactile oddball paradigm for establishing somatosensory BCI-based communication

An emergency call system for patients in locked-in state using an SSVEP-based brain switch.	Lim *et al.* [46]	2017	Experimental Study	Steady-State Visual Evoked Potential	To develop an emergency call system for such patients using a steady-state visual evoked potential (SSVEP)–based brain switch
Clinical feasibility of brain-computer interface based on steady-state visual evoked potential in patients with locked-in syndrome: Case studies.	Hwang *et al.*[47]	2017	Case Report	Steady-State Visual Evoked Potential	To share experiences of SSVEP-based BCI experiments involving five patients with LIS
Steer by ear: Myoelectric auricular control of powered wheelchairs for individuals with spinal cord injury	(Schmalfuß *et al.*[48]	2016	Experimental Study	EMG	To develop a myoelectric auricular control system (ACS) based on bilateral activation of the posterior auricular muscle
An independent SSVEP-based brain-computer interface in locked-in syndrome	Lesenfants *et al.*[49]	2014	Experimental Study	EEG (SSVEP)	To develop an independent SSVEP-BCI based on covert attention

Medical tongue piercing - development and evaluation of a surgical protocol and the perception of procedural discomfort of the participants.	Bentsen *et al.*[50]	2014	Qualitative Study	Tongue Piercing	To develop a protocol for safe insertion of tongue piercing and observing post-procedural observations of participant complications such as bleeding, edema, and infection
Hybrid EEG/EOG-based brain/neural hand exoskeleton restores fully independent daily living activities after quadriplegia	Soekadar *et al.* [51]	2016	Experimental Study	EEG/EOG	To develop a noninvasive, hybrid brain/neural hand exoskeleton (B/NHE) to open and close paralyzed hand
Meeting brain-computer interface user performance expectations using a deep neural network decoding framework.	Schwemmer *et al.*[52]	2018	Experimental Study	EEG	To develop a new deep neural network decoding framework for BCI systems.

Non-causal spike filtering improves decoding of movement intention for intracortical BCIs.	Masse *et al.* [53]	2014	Experimental Study	EEG/ECoG	To develop an improved filtering technique for EEG signal Processing.
Brain-computer interface with language model-electroencephalography fusion for locked-in syndrome	Oken *et al.* [54]	2014	Experimental Study	EEG	To perform a counterbalanced, interleaved within-subject comparison between an auditory streaming BCI that used beep stimuli, and one that used word stimuli
Neural Point-and-Click Communication by a Person With Incomplete Locked-In Syndrome.	Bacher *et al.* [55]	2015	Experimental Study	EEG	To type using a virtual keyboard using A 96-channel intracortical microelectrode array (Blackrock Microsystems Inc, Salt Lake City, UT) surgically implanted in the arm/hand area of her motor cortex of the subject.

Ethical Considerations in Ending Exploratory Brain-Computer Interface Research Studies in Locked-in Syndrome.	Klein, Peters and Higger [56]	2018	Experimental Study	EEG	To study presents case of an individual with presumed LIS enrolled in an exploratory BCI study. Study was done to consider whether two common ethical frameworks for stopping randomized clinical trials—equipoise and nonexploitation—can be usefully applied to elucidating researcher obligations to end exploratory BCI research.
A novel spelling system for locked-in syndrome patients using only eye contact.	Kopsky *et al.* [57]	2014	Experimental Study	EEG	To develop and evaluate a novel spelling system for patients with locked-in syndrome: patients with tetraplegia, not able to talk, and only able to blink their eyes using EEG.

Comparison of eye tracking, electrooculography and an auditory brain-computer interface for binary communication: a case study with a participant in the locked-in state.	Käthner, Kübler and Halder [58]	2015	Case Study	EOG,EEG, Eye Tracking	To study electrooculography (EOG), an eye tracker and an auditory brain-computer interface (BCI) as access methods to augmentative and alternative communication (AAC)
Noninvasive brain-computer interface enables communication after brainstem stroke.	Sellers, Ryan and Hauser[59]	2014	Experimental Study	EEG	To demonstrate that an individual locked in owing to brainstem stroke was able to use a noninvasive BCI to communicate volitional messages by the help of P300-based event-related potential spelling system.
A Novel EMG Interface for Individuals With Tetraplegia to Pilot Robot Hand Grasping.	Tigra *et al.* [60]	2018	Experimental Study	EMG	In this study ability to voluntarily contract a set of selected muscles was assessed in five people with spinal cord-injury through electromyographic (EMG) analysis

Current state of digital signal processing in myoelectric interfaces and related applications	Hakonen, Piitulainen and Visala [61]	2015	Review	-	This review discusses the critical issues and recommended practices from the perspective of myoelectric interfaces
Hybrid BCI Coupling EEG and EMG for Severe Motor Disabilities	Rouillard *et al.* [62]	2015	Experimental Study	EEG,EMG	To develop a data processing and classification technique to detect right and left hand movement.
Tongue-Controlled Computer Game: A New Approach for Rehabilitation of Tongue Motor Function	Kothari *et al.* [63]	2014	Experimental Study	Tongue Drive System (Tds)	To investigate the influence of tongue disability, age, and sex on motor performance for a tongue-training paradigm involving playing a computer game using the Tongue Drive System
A survey on different human-machine interactions used for controlling an electric wheelchair	Ghorbel, Amor and	2019	Review	Smart Wheelchair	To present a survey on different human-machine interactions used for controlling an electric wheelchair

	Jallouli [64]				
Review of assistive strategies in powered lower-limb orthoses and exoskeletons	Yan *et al.* [65]	2015	Review	Exoskeletons	To provide a systematic overview of the assistive strategies utilized by active locomotion–augmentation orthoses and exoskeletons
Upper limb sensorimotor restoration through brain–computer interface technology in tetraparesis	Bockbrader, [66]	2019	Experimental Study	EEG	To demonstrate clinical trials with individuals with paralysis to perform dexterous control of grasp using either robotic neuroprosthetics or neuromuscular stimulation orthotics controlled by intracortical BCI systems
An Electrooculography based Human Machine Interface for wheelchair control	Choudhari AM	2019	Experimental Study	EOG	To propose a robust system that generates control command using only one type of asynchronous eye activity (voluntary eye

					blink) to navigate the wheelchair without a need of graphical user interface.
Perceptions on well-being at home of families with people with disabilities: A psycho-environmental perspective	Labbe D, Jutras S, Coulombe S. [67]	2017	Survey	Review	To conduct interviews with 31 people with spinal cord injury (SCI) and their families. The interviews adressed their perceptions of how their dwellings were promoting or hampering their well-being
Spinal Cord Injury: Scenario in an Indian State	Mathur *et al.*[7]	2014	Prospective Observational Study	--	Prospective observational study about spinal cord injury
Functional priorities, assistive technology, and brain-computer interfaces after spinal cord injury	Collinger *et al.* [1]	2014	Prospective Observational Study	--	To do a survey about Functional priorities, assistive technology, and brain-computer interfaces after spinal cord injury

Flight Simulation using a Brain-Computer Interface: A Pilot, Pilot Study	Kryger *et al.* [68]	2016	Pilot Study	EEG	The purpose of this pilot study was to determine whether proposed BCI system, which involves decoding the signals of two 96-microelectrode arrays implanted into the motor cortex of a subject, could also be used to control an aircraft in a flight simulator environment
An Electrocorticographic Brain Interface in an Individual with Tetraplegia	Wang *et al.*[69]	2014	Experimental Study	ECoG	To investigate the feasibility of an electrocorticography (ECoG)-based BCI system in an individual with tetraplegia caused by C4 level spinal cord injury.
Classification of Wheelchair Commands using Brain Computer Interface: Comparison between Able-Bodied Persons and Patients with Tetraplegia	Chai *et al.* [70]	2014	Experimental Study	EEG	To present a three-class mental task classification for an electroencephalography based brain computer interface.

Electrooculography Based iOS Controller for Individuals with Quadriplegia or Neurodegenerative Disease	(O'Bard *et al.*)	2017	Experimental Study	EOG	To present a low-cost commercial off the shelf (COTS) assistive communication device to allow individuals with quadriplegia to access iOS based devices through electrooculography signals captured from their eye movements
Development of a dual control system applied to a smart wheelchair, using magnetic and speech control.	Ruíz-Serrano *et al*[71]	2014	Experimental Study	Smart Wheelchair	To develop a speech control system and a magnetic control system to drive a wheelchair as an alternative for patients with severe disabilities.
A wavelet- and neural network-based voice system for a smart wheelchair control	AL-Rousan and Assaleh [72]	2008	Experimental Study	Voice Commands Based Smart Wheelchair	To present a design of an automated powered wheelchair system that integrates three techniques (a joystick, direction buttons, or voice) to assist users with motor disability in moving around and

					sending help messages to four distinct destinations using SMS message
The physical and psychological impact of using a computer-based environmental control system: a case study	Squires *et al.* [73]	2014	Case Study	--	To find impact of using computer based control environment
Persons with Multiple Disabilities Choose Among Environmental Stimuli Using a Smile Response and a Technology–Aided Program	Lancioni *et al* [74]	2014	Experimental Study	Face Gestures	To extend the evaluation of the smile response and optic microswitch to choose the preferred stimuli.
The design and evaluation of a peripheral device for use with a computer game intended for children with motor disabilities	Scardovelli and Frère [75]	2014	Experimental Study	Webcam	To develop and test video game which uses peripheral access device consisting of a webcam and a supervisory system that processes the images, for

TongueWise: Tongue-Computer Interface Software for People with Tetraplegia	Caltenco, Andreasen Struijk and Breidegard [76]	2010	Experimental Study	Tongue Movements	To present TongueWise: a software developed for a tongue computer interface that can be activated with the tip of the tongue and that provides direct input that covers most of the standard keyboard and mouse commands
Design of inductive sensors for tongue control system for computers and assistive devices	Lontis and Struijk [77]	2010	Experimental Study	Tongue Movement Sensor	To introduce a novel design of air-core inductive sensors in printed circuit board (PCB) technology for a tongue control system.
A multiple camera tongue switch for a child with severe spastic quadriplegic cerebral palsy	Leung and Chau [78]	2010	Experimental Study	Camera For Tongue Movements	To propose a video-based access technology that facilitated a non-contact tongue protrusion access modality for a 7-year-old boy with severe spastic quadriplegic cerebral palsy

Microswitch Technology for Enabling Self-Determined Responding in Children with Profound and Multiple Disabilities: A Systematic Review	Roche *et al.* [79]	2015	Systematic Review	Micro Switch Technology	To perform review of studies reporting on the use of microswitch technology
Results of the first interim analysis of the RAPPER II trial in patients with spinal cord injury: ambulation and functional exercise programs in the REX powered walking aid	Birch *et al.* [80]	2017	Cohort Study	--	To investigate the feasibility, safety and acceptability of using the REX self stabilizing robotic exoskeleton in people with spinal cord injury (SCI) who are obligatory wheelchair users

Table 1: Descriptive analysis of studies included in the present literature review

2.2 Current state of the art

Our review of the literature revealed that the most commonly used technology for developing SHD is based on physiological signals. The second most frequent approach is motion tracking-based devices, followed by mechanical motion, face recognition, and multi-modal methods. Only a few studies focused on the development of exoskeletons too.

After establishing a very broad state of the art we reviewed all of these approaches to develop SDHs in detail.

2.2.1 Physiology based devices:

Physiological signals can be used to control devices by detecting and processing biological signals from the body. The use of these signals in the development of SHD provides a non-invasive and convenient way for individuals with physical disabilities to control devices and improve their quality of life. These devices have been shown to be effective in helping individuals with disabilities to perform various tasks, such as grasping objects, controlling prosthetic limbs, and even operating wheelchairs

2.2.1.1 Electroencephalography (EEG) Based Devices

Electroencephalography (EEG) functions as a technique for recording and assessing the brain's electrical activity. It gauges the electrical signals generated by neurons in the brain. EEG has found extensive application across diverse fields, including neuroscience, clinical psychology, and medicine. In the medical realm, EEG aids in diagnosing neurological conditions such as epilepsy, sleep disorders, and head injuries. In psychology, EEG is instrumental in studying brain activity during various mental states like sleep, alertness, and meditation. In the domain of neuroscience, EEG is a valuable tool for probing brain function and its temporal dynamics. Moreover, EEG plays a pivotal role in developing brain-computer interfaces (BCIs) and assistive devices (SHDs) tailored for individuals with disabilities.

These EEG-based BCIs and SHDs offer novel avenues for enhancing device control and daily activities for people with diverse disabilities.

This mode of signal extraction holds particular significance for the design of SHDs. Neurons in both the central and peripheral nervous systems emit action potentials, which can be detected via scalp recordings. Different brain regions are responsible for distinct tasks, leading to variations in electrical activity based on the task at hand. Consequently, specific patterns of electric signals emerge for different activities. To harness these signals for SHD development, efficient signal classification is essential. However, categorizing these signals presents challenges due to the limited spatial resolution [40][68].

The utilization of EEG signals for advancing SHDs faces several obstacles. Primary among these is the presence of considerable noise in EEG signals, complicating accurate classification. While employing invasive electrodes instead of scalp electrodes can yield better results, it also introduces complications [31]. Furthermore, the existing EEG signal extraction devices are non-portable and often lead to user discomfort, potentially causing patients to reject these devices due to aesthetic concerns. Nevertheless, technological advancements have led to the availability of compact devices that employ techniques such as machine learning, advanced filtering, sophisticated feature extraction, and wireless electrodes [20][53]. Despite these strides, challenges persist, including complex calibration procedures and low signal consistency [1][68].

Implementing single-command systems is simpler compared to multi-command systems, as recognizing multiple commands can diminish system efficiency. Enhancing system efficiency when processing multiple signals to identify tasks poses a technical challenge. However, classification accuracy can be improved by strategically placing electrodes in specific locations. This allows for simultaneous extraction of multiple signals and pattern combination to identify particular tasks [69]. Yet, this endeavor is not without its challenges, as even minor shifts in electrode placement can significantly impact classification algorithms. High-density electrode grids and microelectrode arrays can enhance signal extraction while minimizing noise. By integrating EEG signals with ocular indicators like blinks or eye movements, hybrid devices can be developed to execute multiple tasks. EEG technology holds promise in various fields such as rehabilitation, gaming, cognitive keyboards, and smart mobility aids [14][40][68][81][82].

While some scholars suggest the development of novel, user-friendly devices, in countries like India where potential users often have limited financial resources [7], it may be more practical to focus on adapting existing devices rather than creating entirely new ones, given the high cost of development.

2.2.1.2 EMG Based SHD

Electromyography (EMG) is a method employed to gauge the electrical activity emanating from muscles during their contractions. These EMG signals furnish valuable insights into muscle functionality, activation sequences, and the harmonization of muscle clusters during motion. Electrodes facilitate the collection of EMG signals, which may comprise either surface electrodes affixed to the skin overlaying the muscle or needle electrodes introduced into the muscle tissue.

EMG signals find diverse applications encompassing clinical and investigative domains. In clinical contexts, EMG signals contribute to diagnosing and monitoring neuromuscular disorders like muscular dystrophy, amyotrophic lateral sclerosis (ALS), and myasthenia gravis. In research settings, EMG signals facilitate the analysis of human movement and neuromuscular performance, offering understanding into muscle activation tendencies and the underpinnings of muscle fatigue and injury. Additionally, EMG signals hold the potential to govern prosthetic devices, affording a natural and intuitive avenue for maneuvering artificial limbs based on the user's muscular activity.

Relative to other biological signals, the EMG signal boasts an enhanced noise-to-signal ratio. Yet, its scope is constrained by the subject's physical state. Consequently, it may not be suitable for all individuals with quadriplegia or motor impairments. Despite this limitation, EMG-based systems present merits such as reduced user attention demand compared to systems like EOG and EEG, coupled with minimal command latency, rendering them more personalized and less susceptible to ambient noise [18][48][61].

Developing wearable devices hinged on EMG signal-based systems can incorporate electrodes discretely positioned beneath clothing or embedded within fabric, empowering users to execute control commands through subtle muscle contractions. This concealment feature renders these devices inconspicuous, preserving user privacy and fostering sustained usability. Nonetheless, the principal challenge of EMG signal-based systems remains the nuanced classification of diverse commands originating from a singular electrode set, leading to diminished command classification accuracy in scenarios involving distinct signal patterns. While mathematical transformations can bolster classification outcomes, EMG systems remain influenced by the physical conditions of the quadriplegic populace [48].

Alternatively, isolated anatomical positions can yield untainted EMG signals devoid of interference from neighboring muscles. As an illustration, by focusing on the posterior auricular muscle, researchers succeeded in capturing EMG signals from both sides of the head via unilateral and bilateral muscle contractions, thus regulating a smart wheelchair [48]. This approach surpasses similar devices in terms of swiftness and precision, exhibiting diminished potential for misinterpreted or unrecognized commands. Achieving voluntary control over these muscles necessitates structured training regimens, while monitoring muscle force offers supplementary insights to potentially amplify device performance.

2.2.1.3 Electro-oculographic (EOG) signal based systems

In recent decades, Electrooculography (EOG) signals have emerged as a valuable avenue for providing alternative communication methods for individuals facing physical impairments. The appeal of EOG signals lies in their accessibility and ease of capture and processing. Particularly noteworthy is the resilience of nerve fibers connecting facial muscles to the brain, remaining intact even after spinal cord injuries and often being the last to be impacted in degenerative neuromuscular conditions. This attribute renders EOG signals viable and attainable [13][14][19]. Employing an arrangement of superficial electrodes affixed to the face, these signals are harnessed to detect specific eye movements or blinks linked to distinct commands. Applications for this technology span from rudimentary interfaces for computers and smartphones to the operation of intelligent wheelchairs [13][19].

Nonetheless, EOG-based technology is accompanied by certain technical limitations. Firstly, the system might encounter challenges if the user shifts their gaze or turns their head, potentially resulting in unintended command execution [14][61]. Secondly, some scenarios may necessitate users to exaggerate their eye movements or blinking, a practice that can prove fatiguing over prolonged periods of use [14]. This fatigue-induced strain can also divert the user's concentration from the task, leading to errors, rework, frustration, and stress. Lastly, the surface electrodes integral to signal acquisition in these systems can be uncomfortable, lacking aesthetic appeal, and hindered in portability in wired configurations. These factors collectively contribute to potential user reluctance and diminished adherence to these devices.

2.2.1.4 Voice recognition based SHD

Recent years have witnessed remarkable strides in signal processing, giving rise to sophisticated algorithms designed for the intricate processing and extraction of features from vocal signals. This advancement has significantly elevated the efficacy of voice-controlled devices, spanning both clinical and general applications. This technology has found extensive utility within smart home environments, enabling the regulation of environmental factors and electronic devices [71][73][83]. Additionally, its application extends to tailored solutions for quadriplegic individuals, such as steering smart wheelchairs [41][71][72].

Nonetheless, certain obstacles persist, inhibiting the widespread adoption of these devices. Foremost among these challenges is the susceptibility of voice recognition accuracy to environmental influences. Fluctuating conditions can induce stress, frustration, and even pose risks to the user's physical safety if misinterpreted vocal commands trigger abrupt changes in the wheelchair's trajectory or speed [48][71]. While certain systems are designed to counteract background noise, they are most effective in noise-free surroundings, consequently curtailing user mobility. Furthermore, the temporal gap between issuing a voice command and the subsequent execution of the task by the wheelchair may not align with immediate expectations, potentially hampering responsiveness in critical scenarios [61][72][73].

Moreover, voice-control systems hinge significantly on calibration, necessitating users to ensure that calibration procedures replicate the intended usage environment and to recalibrate whenever environmental conditions shift.

While some researchers have harnessed voice-controlled systems to cultivate Human-Computer Interaction (HCI), unhindered cursor control remains a challenge. Consequently, these systems typically center on specific functions like launching applications, composing messages, or engaging in particular games. Despite these limitations, voice-control technology remains a promising arena of exploration. Continuous advancements in real-time processing and recognition precision hold the potential to yield more dependable and user-friendly devices [72][73].

2.2.1.5 Motion-tracking and face-gesture recognition-based SHD

Assistive technologies have emerged as indispensable tools for individuals grappling with severe motor disabilities, furnishing them with the capability to govern an array of devices including computers, smartphones, and wheelchairs. A prevalent technology within this domain is motion-tracking systems, adept at monitoring movements of distinct body parts, such as eyes, tongue, or markers positioned on the face. These systems predominantly facilitate Human-Computer Interaction (HCI) via a camera embedded within the computer [40][51]. A notable advantage of these systems lies in their real-time data processing and recognition of facial gestures, enabling users to manipulate devices sans external accessories, fostering comfort and adoption [40][51]. However, the conventional cameras utilized in these setups might encounter challenges in instances of drastic environmental lighting shifts or rapid user motions [21][40][51]. Calibration is a customary prerequisite before deploying these systems, and recalibration becomes necessary if markers or the head undergo significant displacement. Notably, when leveraging eye movements as markers, intricacies arise from potential interference between interaction motion and natural eye motion [52].

Motion-tracking devices centered on tongue motion have also exhibited commendable performance in controlling cursor movements and text inputs. These devices, typically embedded within dental retainers, offer nearly imperceptible integration [51][52]. Nevertheless, the insertion of an external device into the oral cavity may hinder speech functions and present hygienic concerns [55][56]. This limitation is a recurring challenge among all tongue-based technologies, which has prompted exploration into implantable oral devices. Adoption, however, necessitates meticulous medical supervision due to the invasive nature of piercing insertion, associated with potential risks such as dental enamel chipping, periodontal complications, and infections [55][56]. Given the superior performance of tongue-based systems compared to other mechanical and motion-tracking counterparts, they have been earmarked for more intricate tasks such as overseeing entire computers, smartphones, or smart wheelchairs [24][57][58].

Proposals encompass facial and gesture recognition-based systems, tailored for multifarious HCI [21][51]. A straightforward design delineating three regions of interest, with each area linked to a specific function, has proven efficacious for individuals burdened with severe motor limitations. Among individuals with high-level Spinal Cord Injuries (SCIs), residual motor functionality might be confined to facial muscles. In these instances, streamlined devices such as a face recognition unit coupled with a smile-triggered response mechanism offer a means of navigating dynamic menus to perform designated tasks [52][40]. Moreover, ongoing research aims to customize gesture sets in conventional gesture-based systems and adapt existing standard interfaces to enhance suitability, considering that these systems might not optimally accommodate the quadriplegic population.

An innovative study introduces an intriguing approach amalgamating face detection and head motion to capture gesture information for command activation and movement data to regulate cursor displacement [21]. Implementing an infrared depth camera insulates the system from color and illumination fluctuations, thereby conferring an advantage over conventional cameras [21]. Enhanced by a refined randomized decision tree algorithm, the system accurately detects facial features [21]. Leveraging a nonlinear function for identifying nasal position, the system augments user experience in cursor control. It surpasses other systems reliant on gesture recognition and motion-tracking interfaces in precision and speed [21].

Another envisioned advancement centers on body-based power devices that deploy inertial measurement units to estimate minor shoulder motions. This approach facilitates control over translational and rotational facets of a smart wheelchair via Euler angles, angular velocities, and linear accelerations [63][64]. Notably, these devices must prioritize robustness and safety, orchestrating the coordinated execution of diverse components with requisite speed for rotational and translational actions [63][64]. In comparison to Electroencephalography (EEG)-based smart wheelchairs, the body-based power device is less computationally demanding, demands diminished concentration, and boasts a shorter user-training phase [64]. A proof-of-concept experiment involving a smart wheelchair reveals that two degrees of freedom suffice for executing forward-stop and left-right functions, signifying that individuals with residual motor functions can competently oversee a wheelchair with these fundamental controls [63][65]. This discovery holds profound implications, potentially extending to devices governed by these four elemental functions.

2.2.2 Multimodal approach

The integration of a multimodal strategy into the creation of unified devices, proficient in capturing and processing diverse input modes cohesively, has exhibited remarkable potential in streamlining daily activities. This approach not only minimizes the need for a multitude of devices but also enhances resilience, accuracy, and user-friendliness. By adopting this approach, the likelihood of heightened user engagement and improved acceptance of Smart Home Devices (SHDs) is amplified.

Illustratively, the GOM-Face device exemplifies a multimodal creation, harnessing three distinct bioelectrical potentials: glosso-kinetic data for a tongue-operated interface, Electrooculography (EOG) signals for gaze-tracking input, and Electromyography (EMG) potentials to gauge teeth clenching actions [18]. A hierarchical interface architecture was meticulously devised, incorporating discriminative feature extraction and classification methodologies. These techniques identified horizontal tongue and eye movements, as well as states of teeth contraction [84]. The amalgamated data empowered the control of a versatile robot capable of executing multifaceted tasks like walking, dancing, and uttering pre-recorded phrases. Expanding investigations could delve into intricate tongue and eye movements, and potentially integrate this system with Electroencephalography (EEG)-based technologies.

In an alternate approach, a tooth-click detecting device harmoniously merged with a gyrometer-equipped head mouse to govern cursor motion and mouse clicks. The efficacy of this setup surpassed that of voice-controlled systems, given the streamlined nature of the tooth-click mechanism. Unlike speech recognition systems which necessitate signal acquisition, processing, and categorization—culminating in delays prone to inaccuracies during clicking—the gyrometer head mouse proved to be an apt complement to the tooth-click system. The consolidation of these elements into a compact unit eliminates the need for external accessories, enabling seamless usage across diverse computers devoid of frequent calibration requirements.

At its core, the multimodal methodology unveils substantial potential in augmenting the user-friendliness and acceptance of SHDs. Pioneering instances like the GOM-Face device and the tooth-click detecting apparatus underscore the viability of this approach, paving a path for further evolution and exploration within this dynamic field.

2.2.3 Internet of things (IoT)

The Internet of Things (IoT) offers various solutions that can significantly improve the lives of individuals, particularly in terms of entertainment, work, social interaction, and more. Through IoT, people can easily control various aspects of their environment, such as lights and doors. Innovative devices such as automatic beds that can adjust based on the user's clinical condition or those that can transfer a quadriplegic person from a bed to a wheelchair with the help of caregivers can also provide greater independence for those with quadriplegia[85].

However, it should be noted that these devices can be quite expensive, which is a significant disadvantage. As such, more research should be conducted to focus on minimizing the cost of these devices while maintaining their quality and effectiveness in enhancing the lives of people with quadriplegia.

2.2.4 Exoskeletons

Assistive devices are wearable structures that help to enhance and restore human performance for individuals with quadriplegia. These devices are not only limited to quadriplegic individuals but can also be used by people who have partial disabilities or residual upper limb movements. Studies have demonstrated that assistive devices can improve the ability of a quadriplegic individual to walk, stand and sit properly [80]. However, one of the major challenges with assistive devices is their high cost, including the costs associated with maintenance.

2.3 The primary functional and non-functional needs of quadriplegic users regarding the SHD

Functional requirements of quadriplegic individuals have been identified by researchers [33][68][86][87][88][89][90]. The main concerns reported by them are emergency communication, the use of personal computers for academic and work purposes, robotic arms for self-feeding, and smart wheelchairs. In addition to these, urinary and bowel movement controls and upper body controls to stay in a vertical position were also among the main functional requirements [1][86]. Several surveys have been conducted to specifically evaluate the needs of quadriplegic users [33][86], with primary interest to recover natural upper body functions [1]. Additionally, 80% of individuals with quadriplegia were willing to adopt any technology that could restore some grasp functions, while 60% were also ready to accept surgical procedures if the implant could restore some body functions [1][33].

Several studies have identified key interests and concerns of quadriplegic individuals regarding the use of external devices, such as robotic arms, computers, and smart wheelchairs [33][31][1][69][91]. In addition, there is a need for human-computer interface (HCI)-based systems to facilitate communication through email, word processing software for academic and work assignments, and internet browsing, which were identified as the top three priorities for people with quadriplegia in several surveys [79][91]. Improving communication is crucial to enhancing the quality of life for individuals with quadriplegia. Smart wheelchairs, however, raise concerns about misinterpretation of commands, leading to accidents and frustration in users, particularly in emergency situations where delays in recognizing a command can make them feel vulnerable.

Aesthetics of the devices are also a concern for quadriplegic individuals. If a device is not aesthetically pleasing or reliable, it is less likely to be used [92][61][17]. Interestingly, in some studies, invasive devices were more accepted than non-invasive devices due to aesthetic concerns [1][88].

When asked about their primary goals after suffering a spinal cord injury (SCI), quadriplegic individuals identified several key goals.

Quadriplegic individuals express a desire to regain their independence and return to a normal life. This includes being able to perform tasks without assistance and having the opportunity to work again, which serves as motivation for their use of assistive devices [33]. Additionally, these individuals express a desire to adjust to their injury, overcome their physical limitations, and accept their condition [89]. Another primary goal is learning new skills, which brings a sense of fulfillment and enjoyment. Assistive devices should facilitate learning new skills since quadriplegic individuals may lack the ability to perform different tasks [33].

Quadriplegic individuals express a desire to live a meaningful life and participate in social activities, which can improve their quality of life [33] [89]. Increasing their independence through the use of assistive technologies, such as Smarthomes, can improve their self-worth, happiness, and confidence [73]. Smarthomes can help quadriplegic individuals with daily tasks such as lighting control, answering phone calls, and opening and closing doors, reducing the burden on caregivers. In fact, 81% of quadriplegic individuals living in smart homes reported a reduction in caregiver burden and 21% were able to live alone [73][89].

There are two major considerations for SHD design when it comes to disabled individuals. Firstly, the SHD should be personalized to address the specific needs of each individual and have the ability to adapt to specific circumstances [85][38][20]. Secondly, the device should be self-sufficient, capable of managing its operations on its own without the requirement of caregivers. This includes the ability to self-calibrate, self-optimize, and self-protect [85][93].

2.4 Main barriers in the development of SHDs for quadriplegic people

The rate of abandonment of SHDs is high, as reported by various studies [73][38]. When caregivers of quadriplegic individuals were surveyed to determine the main barriers to the use of SHDs, the following results were obtained:

- 37% of respondents cited the high cost of the devices
- 22% of quadriplegic individuals felt that the technology did not address their needs
- 20% of respondents believed that quadriplegic individuals would not accept such technologies.

However, it is important to note that these perceived barriers may not align with the actual reasons for abandonment reported by quadriplegic individuals themselves. Studies have found that poor performance, low reliability, failure to meet expectations, lack of training, difficult maintenance, and poor customer support were some of the reasons for abandonment from the end user's perspective [38][73][73][93].

While certain factors such as cost and reliability are quantifiable, feedback from quadriplegic individuals and their caregivers during the device design process is critical for increasing acceptance rates. Studies show that individuals with a more optimistic outlook are less likely to abandon the device if it meets their expectations. Therefore, it is essential to provide clear counseling to quadriplegic individuals about the device's functions and limitations to avoid generating false expectations that may lead to frustration and abandonment of the technology. The design and development team should include individuals from multiple domains, including designers, engineers, doctors, and psychiatrists. Health professionals should evaluate the physical and mental state of the user, and together, the team can identify the functional and non-functional requirements of the SHD. All of this information is essential for designing customized and more efficient devices.

2.5 Research Gaps

Based on the literature review, there are several research gaps that need to be addressed. Firstly, Brain-machine interface-based self-help devices available in the literature do not address the needs of quadriplegic people properly. Additionally, there is a scarcity of research work and available solutions, particularly in developing countries like India where the affected group is mainly industrial workers with limited financial resources. Furthermore, many patients have conveyed that the available devices try to solve their problems using automatic devices, which makes them feel robotic and lack control over their limbs. There is a scarcity of research that addresses this issue. To add further the gaps in research can be summarized as

- Lack of customizability: Many current assistive technologies are not customizable enough to suit the individual needs of quadriplegic people. This may include factors such as comfort, fit, and adjustability of the device.
- Limited focus on user-centered design: The review highlights the importance of involving quadriplegic individuals and their caregivers in the design process of

assistive devices. However, many existing technologies may not have been developed with sufficient input from end-users.

- Cost: While there are many advanced technologies available to help quadriplegic people, they can be prohibitively expensive. There is a need to develop more cost-effective solutions that still address the needs of users.
- Limited effectiveness of current prosthetic devices: While prosthetic devices can be helpful, they often have limited functionality and may not be well-suited for specific tasks or activities. There is a need for prosthetic devices that are more functional and can more accurately mimic the movements of a natural limb.
- Limited availability of research on signal acquisition strategies from quadriplegic individuals: While EMG and EEG signals can be useful for controlling prosthetic devices, current signal acquisition strategies may not be designed with the unique needs of quadriplegic individuals in mind. There is a need to develop strategies that are more comfortable, easy to use, and reliable for this population.

2.6 Research Objectives

Based on the research gaps identified in the literature review, the following research objectives can be formulated:

- To design and develop a novel signal acquisition system that is best suitable for quadriplegic people.
- To use this signal acquisition system to operate SHDs
- To develop a SHD,by using this signal acquisition system, for quadriplegic people to help improve their quality of life.
- To develop a simple and easy-to-operate prosthetic hand that gives the ability to quadriplegic people to grasp common objects.

Chapter 3

Developing a novel signal acquisition system for quadriplegic people

It was clear from the literature review that physiology based signals are most prevalent in developing SHDs for the quadriplegic people. EEG can provide a non-invasive way to record electrical activity in the brain, allowing for the development of brain-machine interfaces (BMIs) that can translate a person's thoughts into actions. This is particularly useful for quadriplegic individuals who are unable to use their limbs to control prosthetic devices. EEG-based BMIs have been shown to be effective for controlling prosthetic hands and arms in research studies[23] [53][62].

EMG, on the other hand, can be used to detect electrical activity in muscles, which can provide information about a person's intended movements. This can be particularly useful for controlling a prosthetic hand or arm, as it allows for more natural and intuitive movement control. EMG-based control systems have also been shown to be effective in research studies [48][60]

Voice recognition-based systems require the user to have intact vocal capabilities, which may not be suitable for quadriplegic individuals. Additionally, these systems can be sensitive to environmental noise and may not be reliable in all situations. Motion tracking and face gesture-based systems require the user to have some level of residual motion or facial control, which may not be feasible for quadriplegic individuals with severe motor impairments. Tongue movement-based systems are an option, but these require a significant amount of training to master and may be uncomfortable or even painful for the user[55][56]. Camera-based systems require the user to be within view of the camera at all times, which may not be practical in all situations, especially for individuals who are bedridden or have limited mobility.

Hence in this present work, studies were conducted to examine EEG and EMG based methods to extract signals for quadriplegic people.

3.1 Experimental study on EEG based methods

The inception of electroencephalography (EEG) dates back to 1924 when Berger et al. first employed it to document cerebral electrical potentials. Since its inception, this technique has unfurled a multitude of research avenues, gaining notable traction over the past two decades. However, the raw electrical signals garnered from subjects are inherently intricate and cannot be directly employed. Consequently, several pre-processing methods are applied to distill pertinent insights from the signals, rendering signal classification a formidable undertaking.

Researchers have endeavored to unravel the genesis of these potentials, their inherent nature, plausible artificial manipulation, and the techniques for identification and prognostication. In practical terms, EEG potentials are recorded through electrodes, which can either be surgically placed on the brain or non-invasively positioned on predetermined scalp locations. Given the intricacy of surgical placement, the non-surgical approach using scalp electrodes is more prevalent. Once recorded, signals undergo filtration to eliminate extraneous noise, environmental artifacts, eye blinks, and electrical interference, constituting the pre-processing phase.

In pursuit of predicting cognitive states, researchers typically filter the electric potential waves within the 0-80 Hz range. Subsequently, feature extraction ensues, revealing that brain-generated potential waves oscillate across multiple frequencies. These oscillations have been categorized into four groups: alpha, beta, theta, and delta waves, spanning frequency ranges of 0-4 Hz, 4-8 Hz, 8-16 Hz, and 16-32 Hz, respectively.

A variety of methodologies have been harnessed for feature extraction, including Power Spectral Density (PSD), Hilbert-Huang Transformation (HHT), Band Power features, Fast

Fourier Transformation (FFT), Discrete Wavelet Transformation (DWT), and the Minimum Energy Combination method. These extracted features are subsequently employed to predict the cognitive state of the user.

Ultimately, the derived features are channeled into classifying brain potentials through methodologies such as Genetic Algorithm (GA), Artificial Neural Networks (ANN), Linear Discriminant Analysis (LDA), and Support Vector Machine (SVM).

An important consideration pertains to the theoretical uncertainties that still surround information processing within the brain. Consequently, there exists a considerable potential for uncontrolled events, statistically speaking, within data collected via scalp electrode placement. The exploration herein seeks to ascertain the presence of such uncontrolled events within scalp-recorded data and gauge the potential impact of their removal on classification accuracy.

3.1.1 Experimental Study and Results

3.1.1.1 Techniques Used

Discrete Wavelet Transform(DWT)

Discrete Wavelet Transformation (DWT) is a mathematical technique used to analyze and decompose signals, such as audio or image data, into different frequency bands. It is a type of wavelet transform that uses a set of wavelets, which are small oscillating waves, to represent the signal in both time and frequency domains.

DWT involves a series of filtering and down-sampling operations that progressively divide the signal into low-frequency (approximation) and high-frequency (detail) components. The process begins with a low-pass filter that removes high-frequency components from the signal, followed by a down-sampling operation that reduces the sampling rate of the signal by a factor of 2. The resulting signal is referred to as the approximation signal.

The high-frequency components are obtained by passing the original signal through a high-pass filter, followed by down-sampling. The resulting signal is referred to as the detail signal. The process is repeated on the approximation signal to obtain further decomposition levels, resulting in a tree-like structure of approximation and detail coefficients.

We used matlab for performing the DWT. Matlab’s Wavedec function was used for the same.Matlab's wavedec function is a built-in function that implements the wavelet decomposition of a one-dimensional signal using the discrete wavelet transform (DWT). The wavedec function is part of the Wavelet Toolbox in Matlab and uses a specified wavelet for decomposition.

The syntax of the wavedec function is as follows: [C, L] = wavedec(X, N, wname)

where X is the input signal, N is the number of decomposition levels, and wname is the name of the wavelet. The function returns two outputs: C, a concatenated vector of the approximation and detail coefficients, and L, a vector containing the length of the approximation and detail coefficients at each level.

Statistical Process Control

Statistical Process Control (SPC) is a method for monitoring, controlling and improving a process by analyzing and interpreting statistical data. SPC is used to monitor and control quality in manufacturing processes, and it can also be applied in other types of processes too. SPC involves the use of a control chart, which is a tool used to monitor a process and detect whether it is in a state of statistical control. An out of control event in a control chart occurs when the process being monitored is exhibiting unusual or unexpected behavior that may indicate that the process is not in a state of statistical control.

We used mean and range charts to find out of control events.Mean and range charts are a type of statistical process control (SPC) chart used in SQC (Statistical Quality Control) to monitor the central tendency and dispersion of a process.In mean and range charts, a point is considered out of control if it falls outside the control limits or if it exhibits any pattern that indicates the presence of special causes of variation.

In order to construct mean ($\overline{X}$) Chart

- Central Line(CL) is obtained by $\overline{\overline{X}} = \Sigma(\overline{X}/g)$
- Upper Control Limit (UCL) for $\overline{X}$ Chart is obtained $UCL_{\overline{X}} = \overline{\overline{X}} + A_2\overline{R}$
- Lower Control Limit (LCL) for $\overline{X}$ Chart is obtained $LCL_{\overline{X}} = \overline{\overline{X}} - A_2\overline{R}$

In order to construct Range (R) Chart

- Central Line(CL) is obtained by $\overline{R} = \Sigma(R/g)$
- Upper Control Limit (UCL) for R Chart is obtained $UCL_R = D_4\overline{R}$
- Upper Control Limit (LCL) for R Chart is obtained $LCL_R = D_3\overline{R}$

Where g, A_2, D_3, D_4 are the number of subgroups and the factors for control limits respectively.

A point can be categorized as out of control in a mean and range chart if it falls in one of the following category:

- Outliers: A data point that falls outside the control limits for either the mean or the range is considered an outlier and is classified as out of control.
- Trend: A series of consecutive points that show an upward or downward trend indicate that there is a systematic shift in the process mean, and the process is considered out of control.
- Shift: A point that is significantly different from the other data points indicates a sudden shift in the process mean, and the process is considered out of control.
- Cycles: A repeating pattern of points indicates that there is a recurring cause of variation in the process, and the process is considered out of control.

Support Vector Machines (SVM):

SVM, or Support Vector Machine, is a type of machine learning algorithm that can be used for both classification and regression tasks. SVM works by finding a hyperplane in a high-dimensional space that best separates the data into different classes. The hyperplane is chosen so that the margin between the closest points from each class is maximized. SVM is especially useful when working with complex datasets with multiple features.

In SVM, the data points are plotted in a multidimensional space, and each point is assigned to a particular class. The algorithm then finds the hyperplane that maximizes the margin between the closest points from each class. The data points closest to the hyperplane are called support vectors.

One advantage of SVM is that it works well with high-dimensional data and is less prone to overfitting than other machine learning algorithms. However, SVM can be computationally expensive and may not work well with very large datasets.

3.1.1.2 Dataset

The dataset used for this study was recorded as per international 10-20 system. The 10-20 system is the most widely used electrode placement system for EEG recording. It defines specific locations on the scalp for electrode placement based on the distance between skull landmarks, with electrodes placed at intervals of 10% or 20% of the total distance between the landmarks [117]. Figure 2 shows the same The dataset was recorded from the C3,C4 and Cz position of a 25-year-old female subject. A screen was positioned in front of her and she was prompted to imagine moving her right or left hand when the corresponding cues appeared on the screen. The dataset was sampled at a frequency of 128 Hz and recorded in accordance with the international 10-20 system. Each trial lasted for 9 seconds, with the participant instructed to remain still for the initial 2 seconds. After 2 seconds, a cue was presented on the screen indicating the start of the trial. A total of 140 trials were recorded.

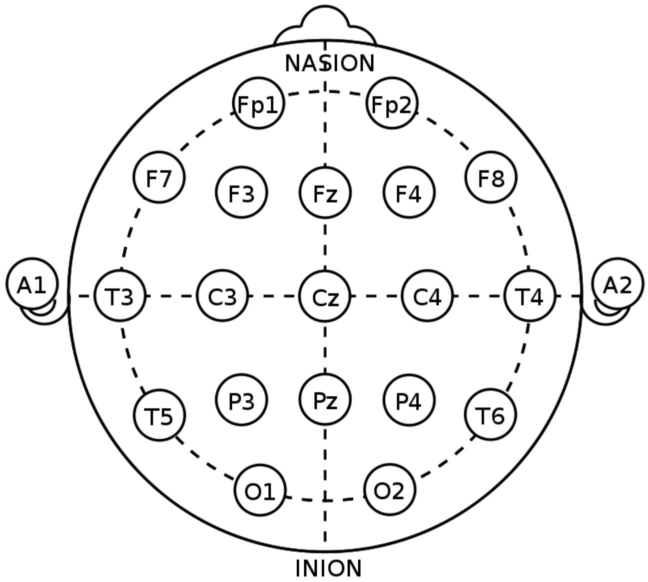


Figure 2 - Specific locations on the scalp for electrode placement as per international 10-20 system

3.1.1.3 Experimental Study

The experimental study employed a methodology that involved several key steps. First, the dataset was pre-processed to prepare it for analysis. Next, features were extracted from the dataset. Two separate datasets were then formed, with one containing out-of-control events and the other excluding such events. Both datasets were classified using a SVM. The accuracy of classification was then compared between the two datasets to determine the impact of out-of-control events on the accuracy of the SVM-based classification. Overall, this methodology allowed for a comprehensive evaluation of the effect of out-of-control events on the accuracy of the classification system, and provided insights into the effectiveness of the SPC-based approach for EEG analysis. Figure 3 shows the process of experimental study.

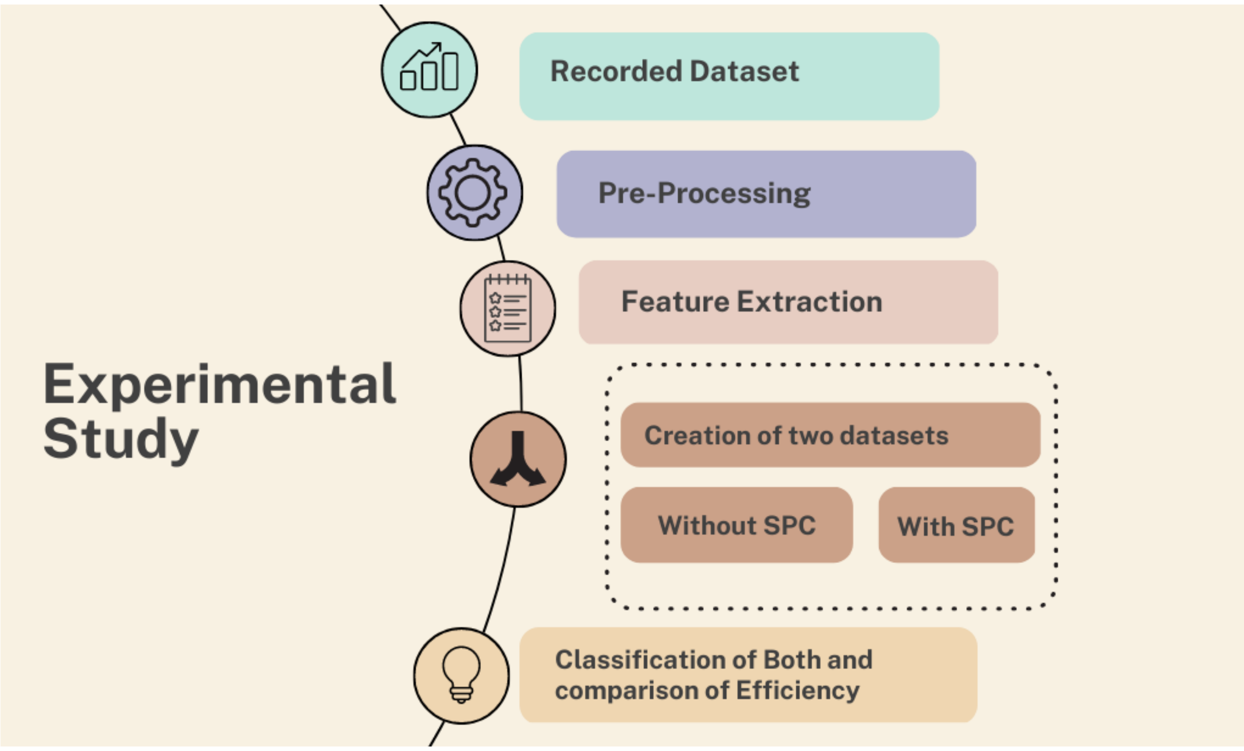


Figure 3: Block diagram showing procedure of experimental study

Pre-Processing

The dataset was sampled at 128 Hz, resulting in 1,152 events per trial. The initial 3 seconds of each trial were disregarded, as no mental task was performed during this period. The remaining 6 seconds of data produced 768 events per trial, which were subsequently processed using Matlab. The data was decomposed using the wavedec function at 4 levels, resulting in one approximation coefficient (Ad) and four detail coefficients (Db, Dc, and Dd). The decomposition tree of the transformation at 4 levels is shown in Figure 2. Further feature extraction was performed using the approximation coefficient Ad and detail coefficients Db, Dc, and Dd.

Feature Extraction and Classification

To extract features, we used the three detail coefficients and one approximation coefficient obtained from the previous process. We calculated the mean of all four coefficients separately. Thus, for a single trial and three channels (C4, CZ, and C3), we obtained four features per channel, resulting in a total of 12 features per trial for all three channels. The extracted features were then used for further analyses. We created two datasets from these extracted features. In one dataset the features were used as it is while in the other dataset the out of control datapoints were identified using the statistical process control and removed from the data. Figure 4 shows the control charts created and identified out of control events.

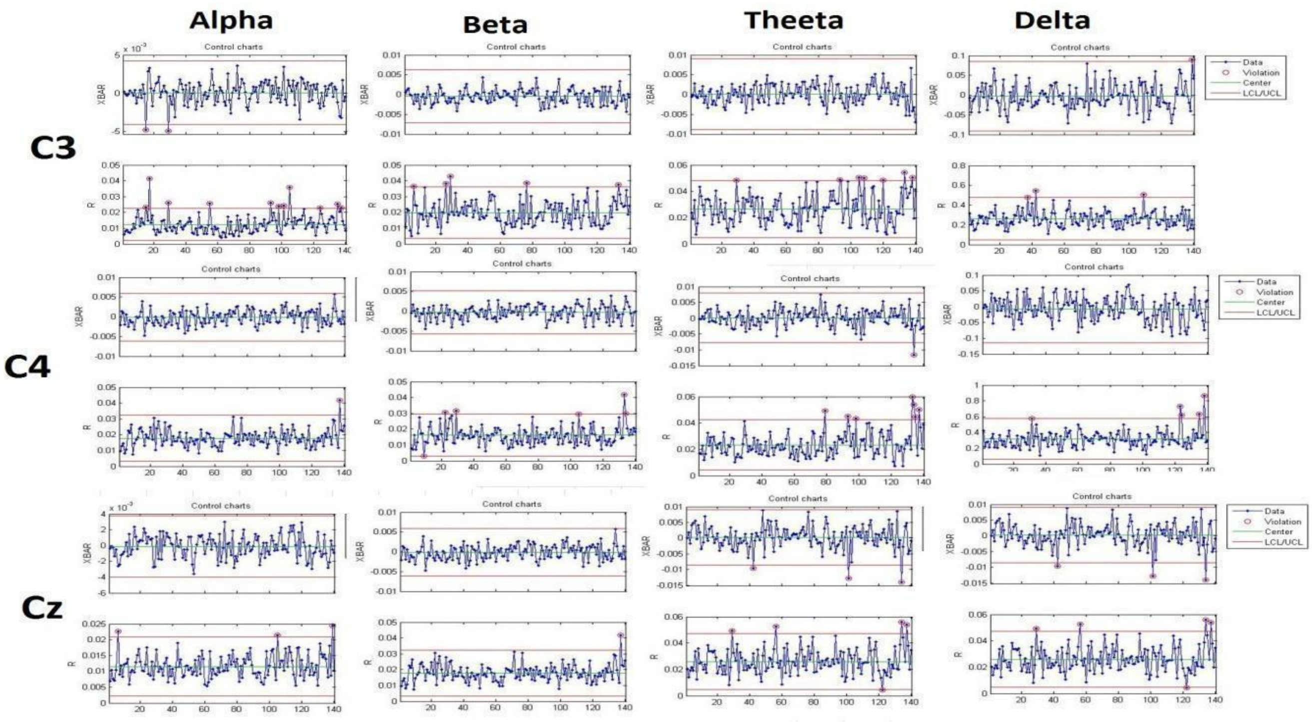


Figure 4 – Mean and Range charts of alpha, beta, theta and delta sub-bands over c3, cz and c4 channels to identify out of control processes.

The classification was done with the help of SVM. The two datasets obtained in previous step were normalized first before feeding it to SVM for classification. We used a 5 step cross validation while doing the classification. Cross-validation is a technique used to evaluate the performance of a machine learning model by splitting the available data into training and testing sets. In 5-fold cross-validation, the data is randomly divided into five subsets of equal size. The model is then trained on four of the subsets and evaluated on the remaining subset. This process is repeated five times, with each subset serving as the test set once. Using 5-fold cross-validation in SVM classification is advantageous for several reasons. Firstly, it helps to avoid overfitting by assessing the model's performance on different subsets of the data. Secondly, it provides a more reliable estimate of the model's performance by averaging the results of five different evaluations. Lastly, it maximizes the use of available data by using each subset of the data as both training and test sets.

The classification accuracy showed a significant improvement when the out of control events were removed from the dataset. The first dataset, which contained out of control events, reported a classification accuracy of 73%, whereas the second dataset, which did not have any out of control events, reported a classification accuracy of 84%. This indicates an increase of 11% in the classification accuracy when the out of control events were removed from the dataset.

To further analyze the classification results, minimum classification error and confusion plots were generated for both datasets. Figure 5 and 6 shows the minimum classification error and confusion plots of the first dataset, while Figure 7 and 8 shows the minimum classification error and confusion plots of the second dataset. These plots provide insights into the performance of the classification model and help to identify any misclassifications that occurred during the classification process. Overall, the removal of out of control events has resulted in a significant improvement in the classification accuracy, which can have important implications for the practical application of the classification model.

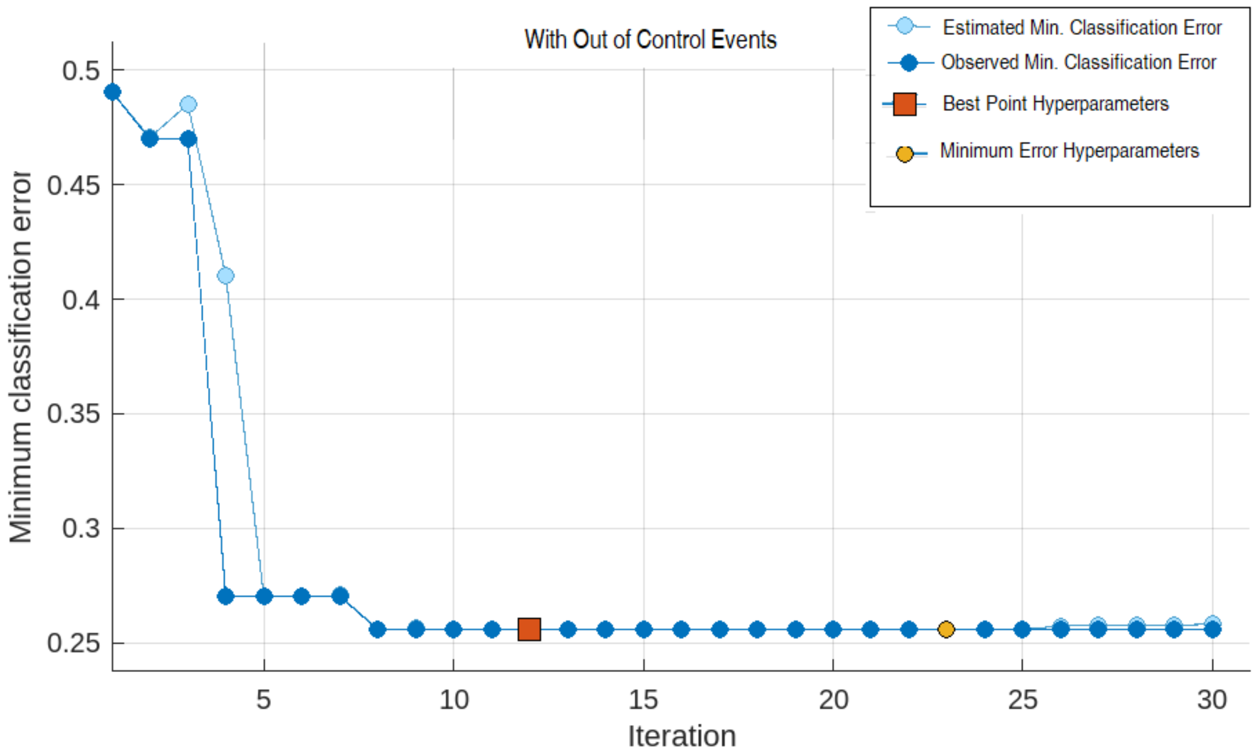


Figure 5: Minimum classification error of data containing out-of-control events

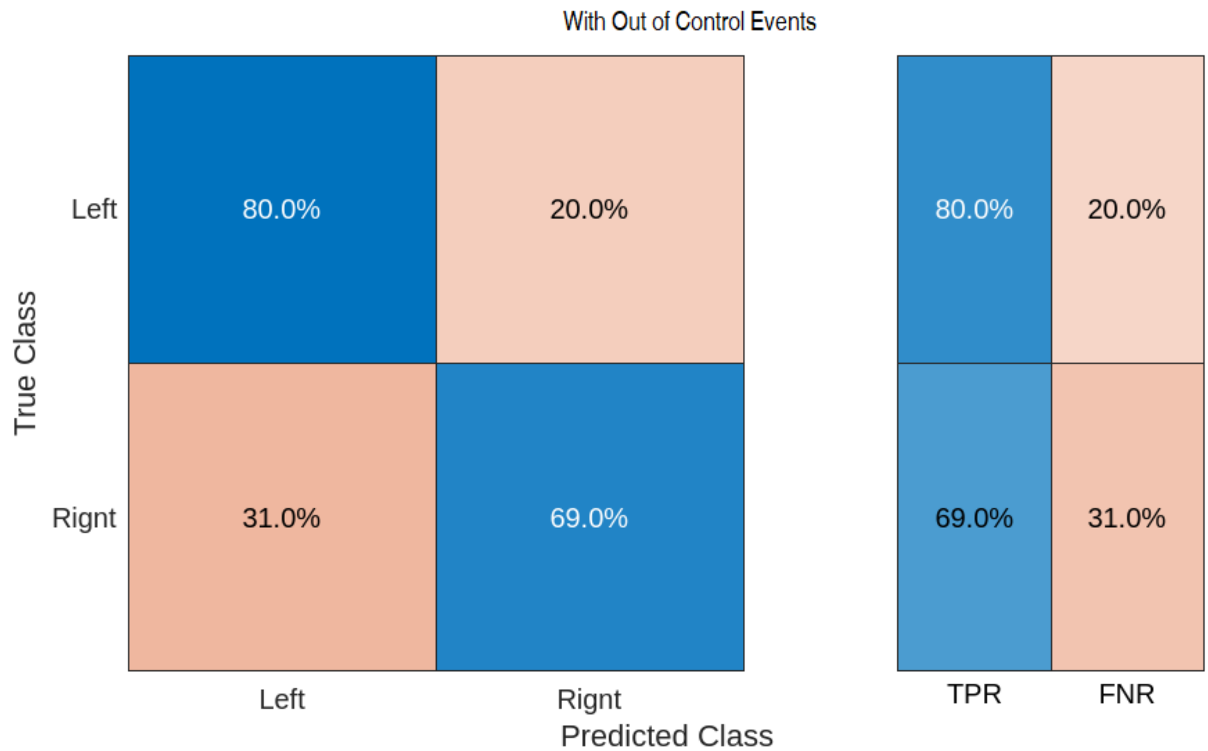


Figure 6: Confusion plots of data containing out-of-control events

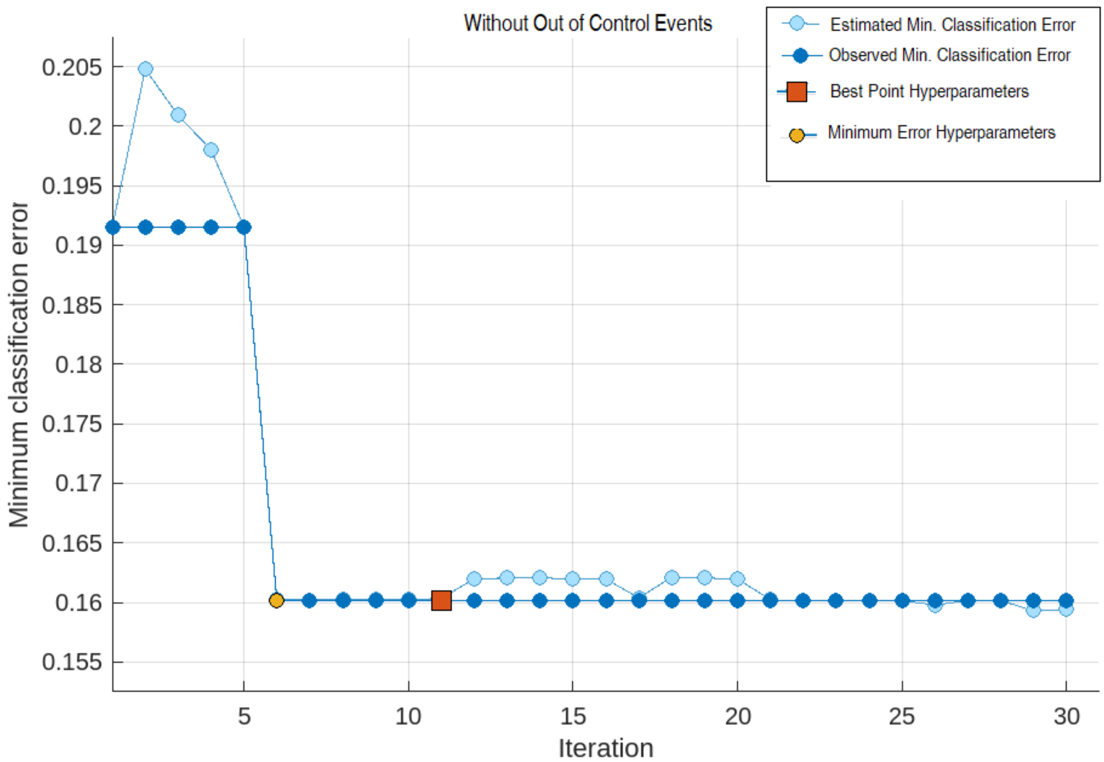


Figure 7: Minimum classification error of data without out-of-control events

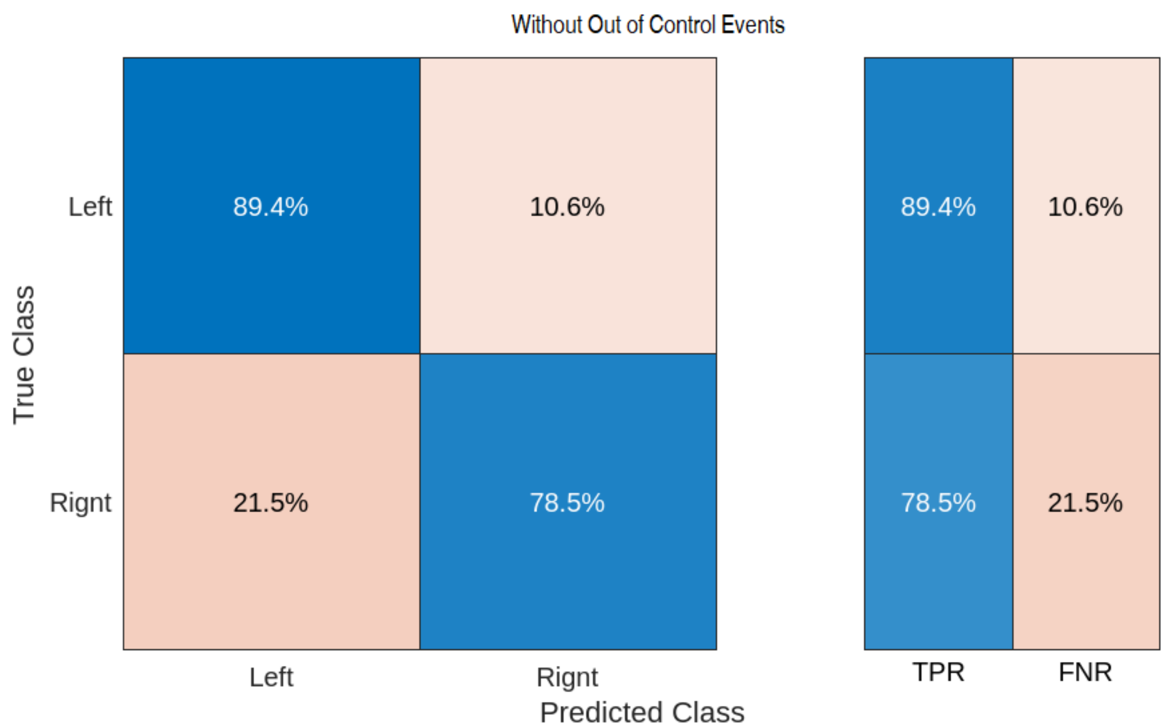


Figure 7 : Confusion plots of data without out-of-control events

3.1.2 Conclusion

In this study we found that the accuracy of EEG based BMI classification can be improved significantly when using a dataset without out of control events. To further improve the results, future studies could focus on increasing the quality of data acquisition by using high-density EEG systems. Additionally, incorporating more channels of EEG data can provide a more comprehensive view of brain activity during the task and may improve classification accuracy.

Despite the promising results of using EEG for developing self-help devices (SHD), it is challenging to use it outside the lab environment due to various factors such as movement artifacts, electrode placement, and signal interference from other sources.

As EMG was also one of the most commonly used methods to develop SHD for quadriplegic people hence we also investigated its effectiveness in the subsequent part of this thesis.

3.2 Experimental study on EMG based methods

In the previous part of this thesis, we explored the effectiveness of EEG in developing self-help devices for quadriplegic individuals. While EEG is a promising method for BMI classification, its use outside of the lab environment is constrained by data quality issues. Therefore, we also investigated the potential of electromyography (EMG) as an alternative method for developing SHDs. EMG has also been widely used for BMI classification in quadriplegic individuals.

Electromyography (EMG) based self-help devices (SHD) offer an alternative solution to quadriplegic individuals who require assistance with activities of daily living. EMG is a technique that records the electrical activity produced by muscles. By using EMG, it is possible to detect the intention of a user to perform a particular movement, such as grasping an object, and translate that intention into a control signal for an SHD. This approach has the potential to provide quadriplegic individuals with greater independence and improve their quality of life.

3.2.1 Experimental Study and Results

3.2.1.1 Techniques Used

Kernel Naive Bayes Classifier:

Kernel Naive Bayes (KNB) is a variant of the popular Naive Bayes classifier that employs kernel methods to improve its performance on complex datasets. The Naive Bayes classifier is a simple but effective probabilistic classification algorithm that is widely used in machine learning applications. However, its performance can be limited in cases where the data is non-linearly separable or has complex decision boundaries. Kernel methods provide a way to transform the input data into a higher-dimensional space where it is more easily separable. KNB applies kernel methods to the Naive Bayes classifier by first mapping the input data into a high-dimensional feature space using a kernel function, and then applying the Naive Bayes algorithm on the transformed data. This approach has been shown to improve the classification accuracy of Naive Bayes on several datasets, particularly in cases where the data has non-linearly separable features.

K-Nearest Algorithm (KNN) :

K-Nearest Neighbors (KNN) is a simple but effective classification algorithm that is widely used in machine learning. KNN works by finding the k nearest training examples to a given test example in the feature space, and then classifying the test example based on the majority class of its k nearest neighbors. KNN is a non-parametric algorithm, which means that it does not make any assumptions about the underlying distribution of the data. KNN is also a lazy learning algorithm, which means that it does not perform any training on the data and instead stores the entire training set for use during classification. KNN is particularly useful in cases where the data is not linearly separable, and the decision boundary is complex.

Linear Discriminant Analysis (LDA):

Linear Discriminant Analysis is a popular classification algorithm that is used for dimensionality reduction and classification tasks. LDA works by projecting the high-dimensional feature space onto a lower-dimensional space while maximizing the separability between classes. This is done by finding the directions (linear combinations of the original features) that maximize the ratio of the between-class variance to the within-class variance. LDA assumes that the data is normally distributed and that the classes have equal covariance matrices. LDA is a parametric algorithm, which means that it makes assumptions about the underlying distribution of the data. LDA is particularly useful in cases where the number of features is larger than the number of training examples, and overfitting is a concern. LDA can also be used for feature extraction, as it provides a way to project the data onto a lower-dimensional space while preserving the discriminative information. However, LDA also has some limitations, such as its sensitivity to outliers and its assumptions about the underlying distribution of the data. Overall, LDA is a powerful tool in the machine learning toolkit that can be used for classification and feature extraction tasks on various datasets.

3.2.1.2 Dataset

Surface EMG recordings were conducted during eyeblinks, on a group of 5 healthy participants, comprising of 3 males and 2 females with an average age of 30.4±2.27 years. The recordings were performed twice daily over two consecutive days, with each recording session lasting from 9:00 am to 5:30 pm and consisting of three sessions, spaced 4 hours apart. The RMS Salus 2C EMG machine, provided by RECORDERS & MEDICARE

SYSTEMS PVT. LTD. in India, was used to capture the surface EMG signals, and the RMS EMG Salus 2C V.7.7.1 software was used for recording. The participants were instructed to sit comfortably on a chair in front of a screen, where they were first presented with a resting message for 20 seconds and then asked to blink voluntarily at specific intervals when prompted by messages displayed on the screen.

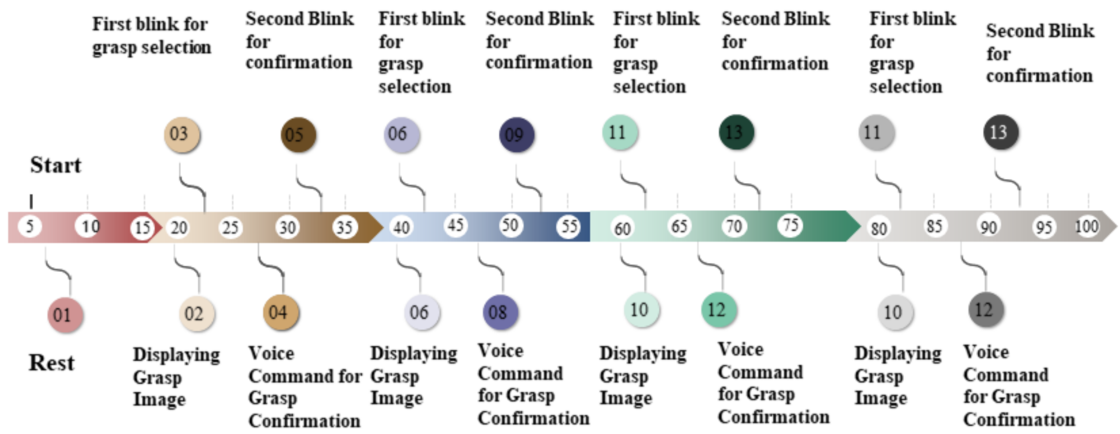


Fig 10: Signal recording trial timeline

Figure 9 : RMS Salus 2c EMG recording machine

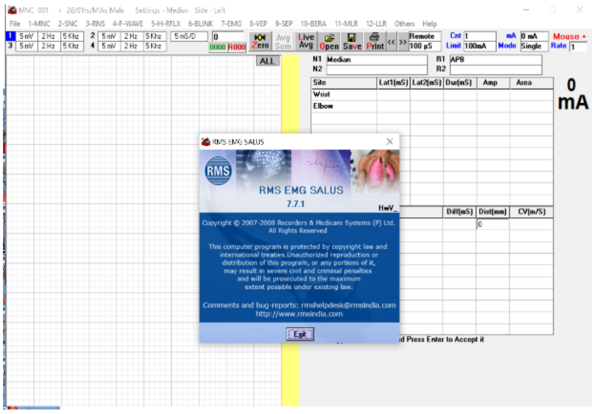


Figure 10: RMS Salus 2c EMG recording Software Salus V.7.7.1.

Figure 11. Volunteers for recording EMG data.

3.2.1.3 Experimental Study

Pre Processing:

To improve the quality of the data, the raw signal was filtered before further processing as it contained a lot of noise. To create a baseline, the data recorded during the initial 20 seconds of resting was used.

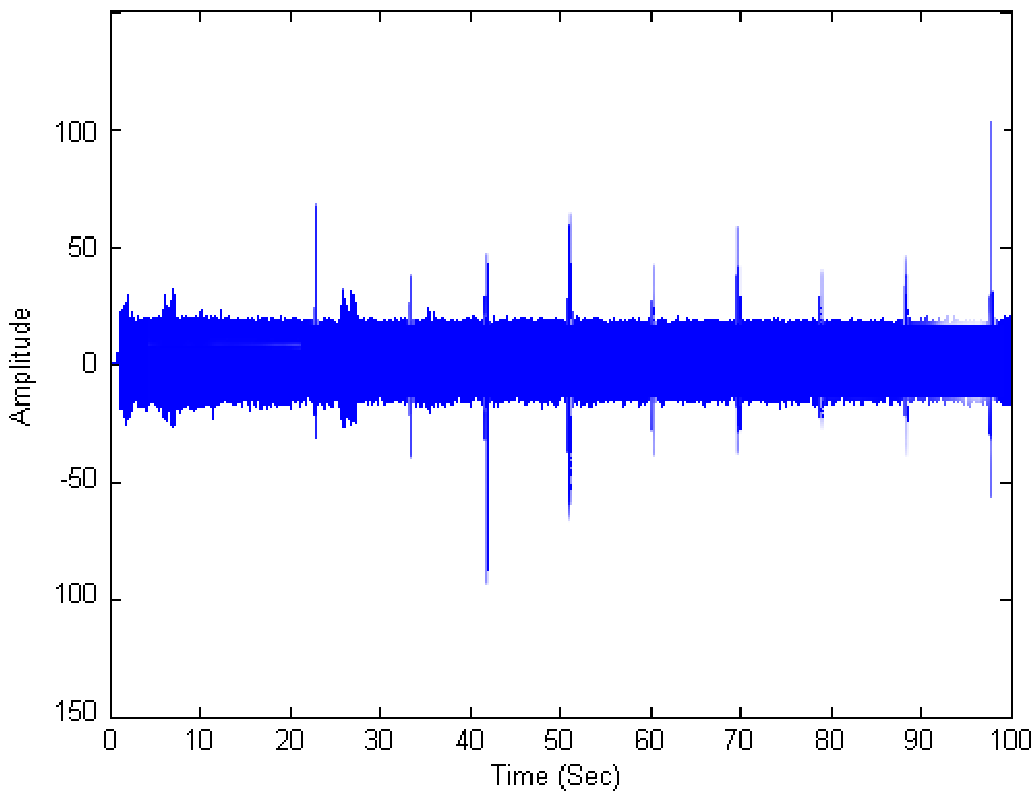


Figure 12: Raw EMG Signal

Next, we converted all negative data points to positive and applied a moving average using a sliding window, as shown in Figures 13 . Finally, we further processed the signal by applying exponential smoothing and normalization between 0 and 1. The resulting smoothed and normalized signal is represented in Figure 14. These filtering and processing steps helped to enhance the prominence of the EMG data related to eyeblinks in the signal.

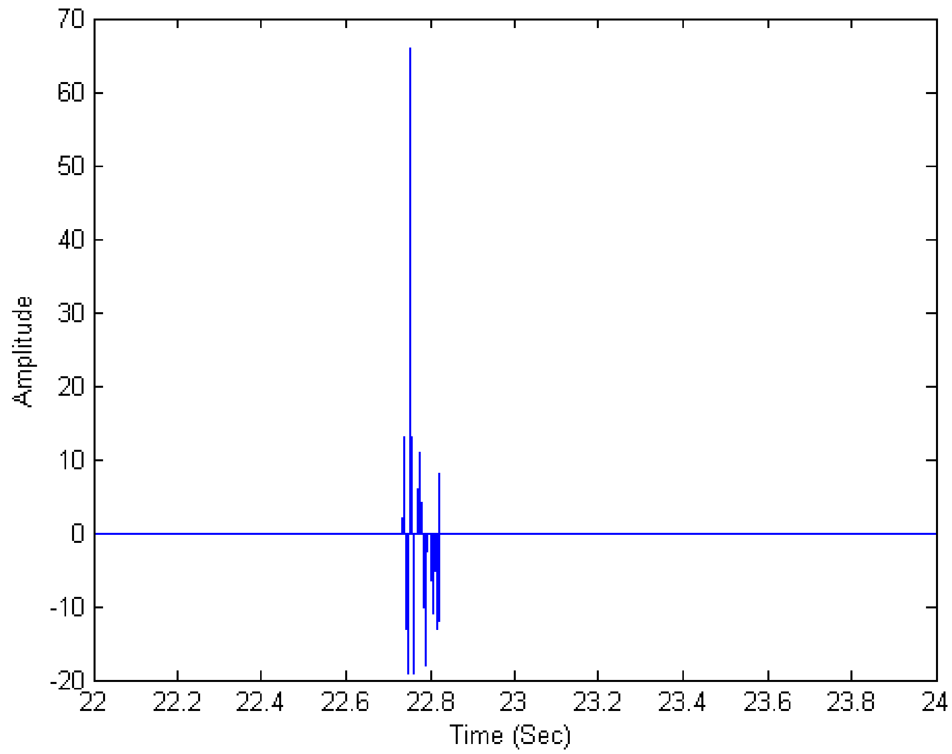


Figure 13: Filtered signal from 22 Sec to 24 Sec recorded from subject representing eye blink

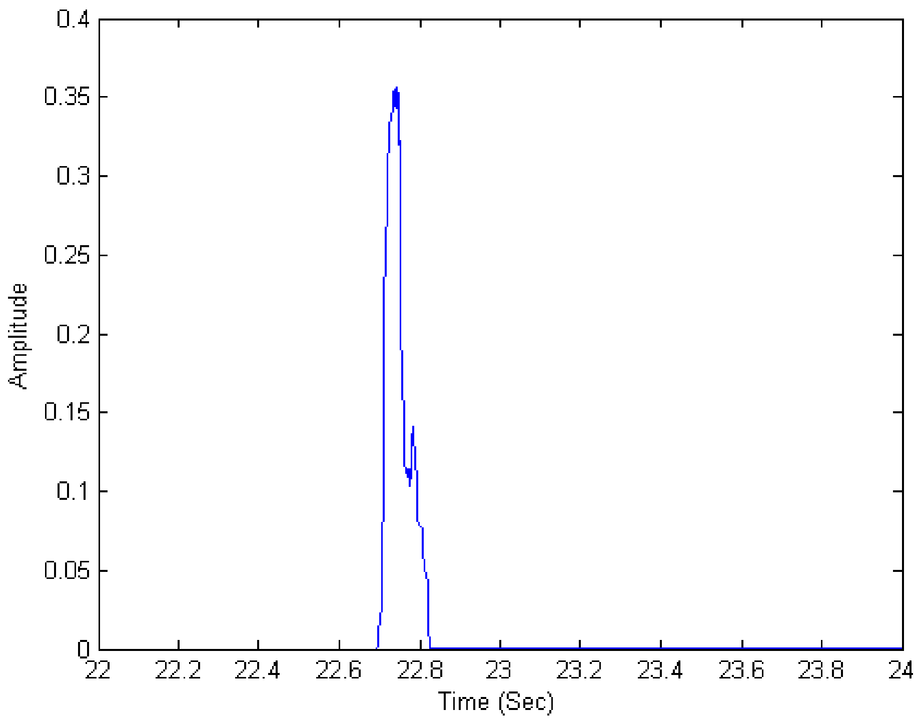


Figure 14: Signal after Pre processing, exponential smoothing and normalizing from 22 Sec to 24 Sec recorded from subject 1 during trial 1 representing eye blink

Feature Extraction and Classification:

The recorded dataset was employed to create a classifier for detecting eye blinks. To accomplish this, the entire dataset was divided into 1-second segments, and these segments were categorized as either containing or not containing eye blinks. Two features, namely mean and standard deviation, were calculated from each 1-second segment. The resulting dataset was organized as shown in Table 2, with the data being labeled according to the recorded timestamps of the blink events. For classification purposes, we employed supervised learning using the labeled dataset.

We used various supervised learning techniques, including Logistic Regression, Naïve Bayes Classifier, k-Nearest Algorithm, and Linear Discriminant Analysis. The classification results are depicted in Figures 15,16,17,18 and 19,20,21,22, showing scatter plots and confusion plots, respectively. The accuracy of all the algorithms used exceeded 98%, indicating that the recorded EMG signals were effective in accurately classifying voluntary eye blinks.

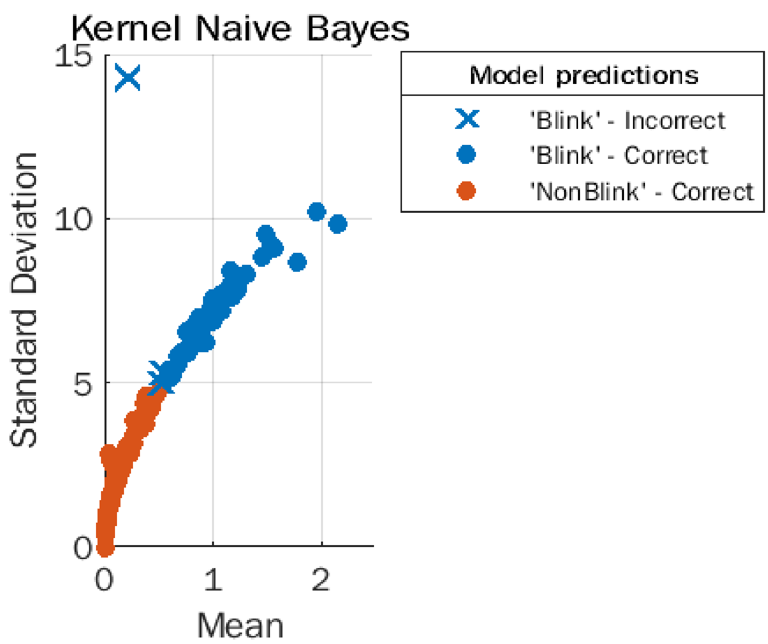


Figure 15: Scatter plots for Naïve Bayes classifier

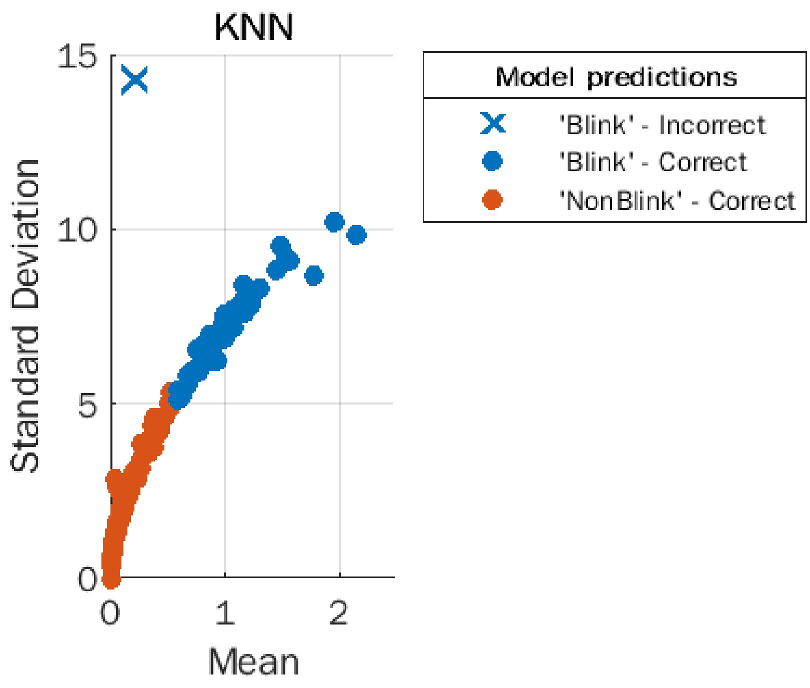


Figure 16: Scatter plots for KNN

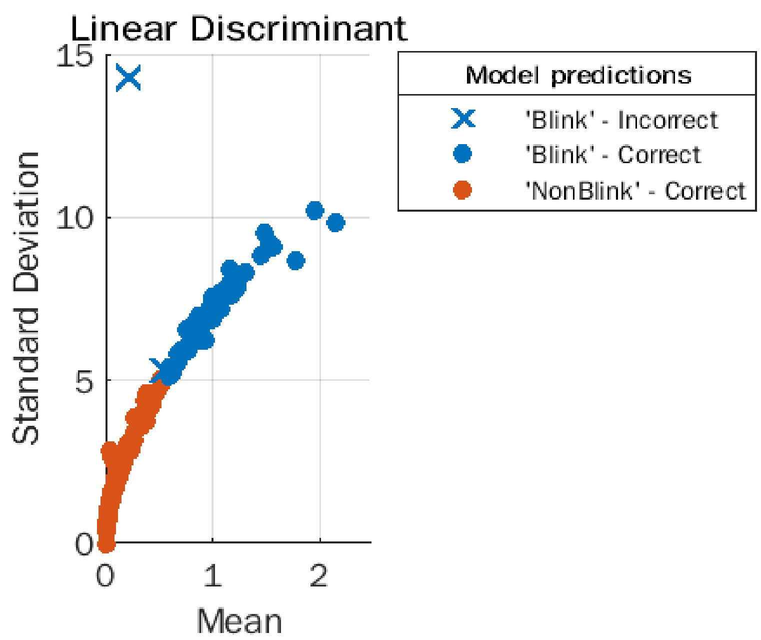


Figure 17: Scatter plots for LDA

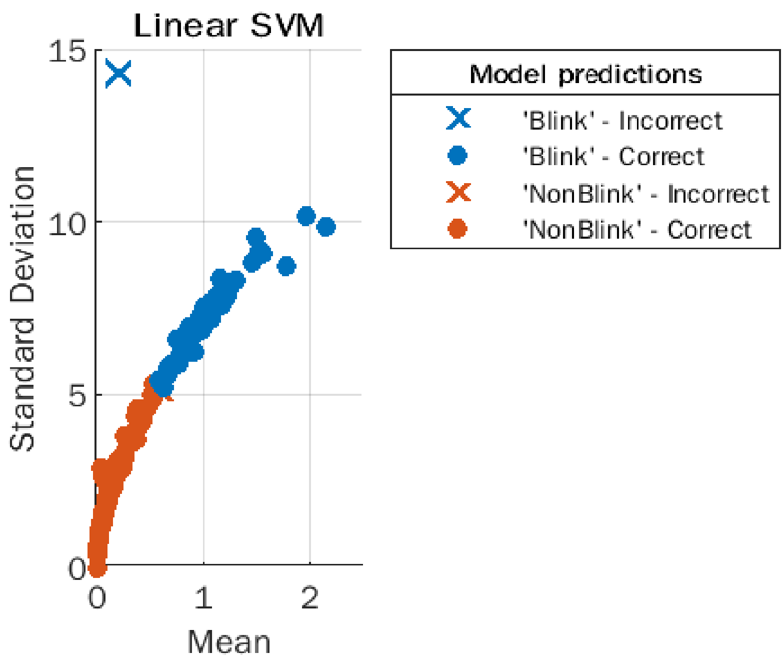


Figure 18: Scatter plots for SVM

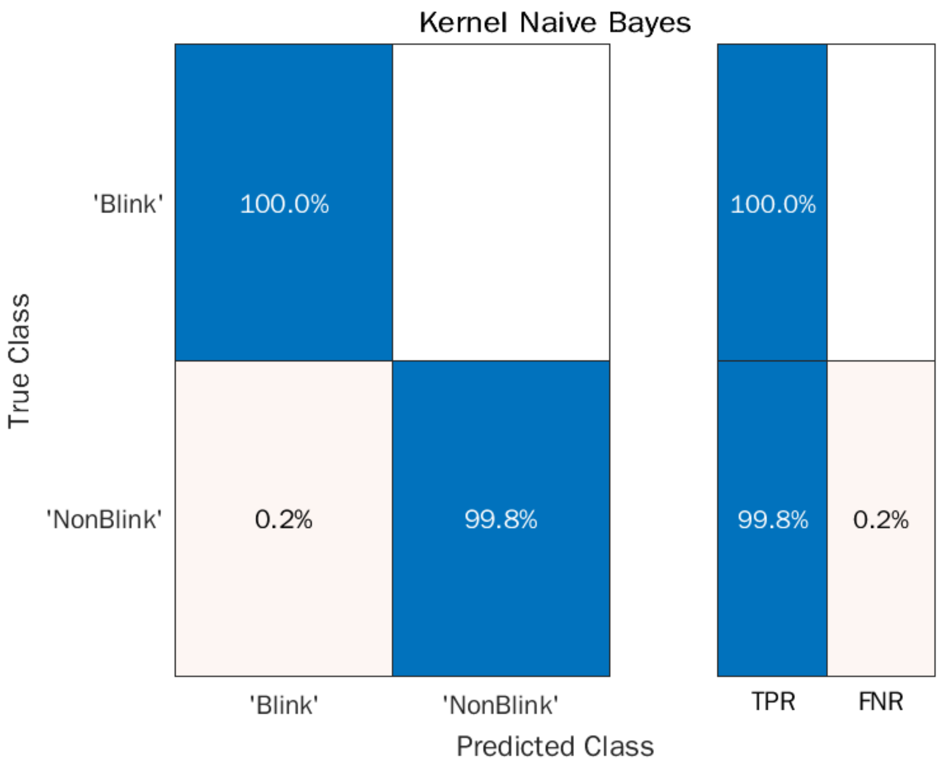


Figure 19: Confusion plots for Naïve Bayes classifier

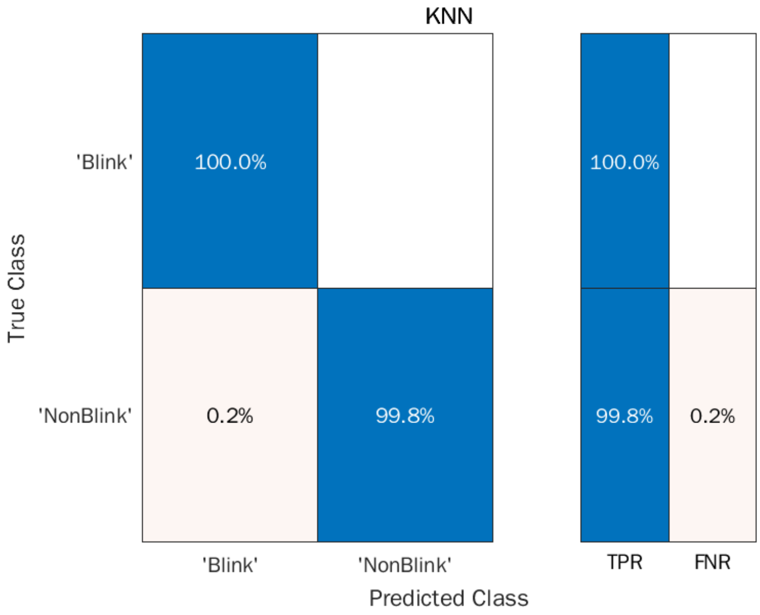


Figure 20: Confusion plots for KNN

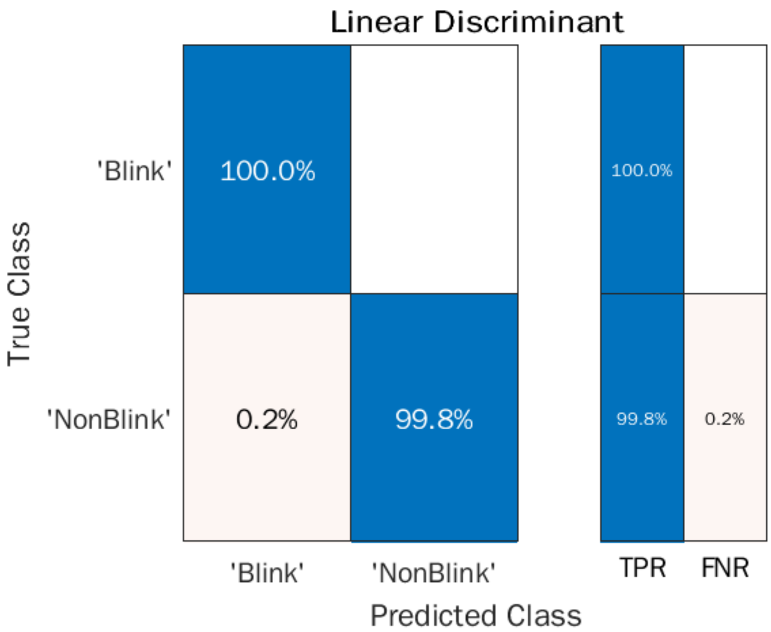


Figure 21: Confusion plots for LDA

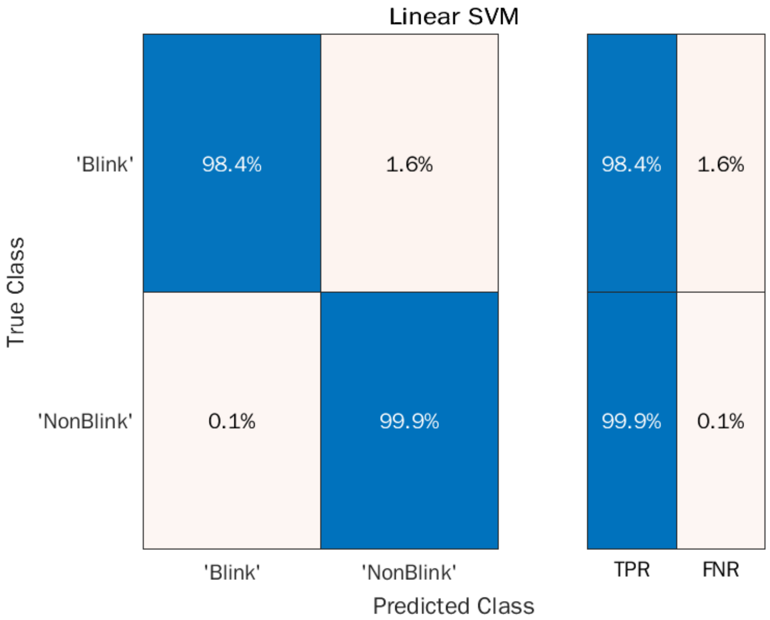


Figure 22: Confusion plots for SVM

3.2.2 Conclusion

In conclusion, the use of EMG as an alternative method for developing self-help devices (SHDs) for quadriplegic individuals has great potential to provide greater independence and improve their quality of life. In this chapter, we investigated the effectiveness of four machine learning techniques, namely Kernel Naive Bayes, K-Nearest Neighbors, Linear Discriminant Analysis, and Support Vector Machine, in classifying EMG signals recorded during eyeblinks. The experiment involved five healthy participants and was conducted over two consecutive days. This study provides further evidence for the potential of effectiveness of EMG in developing SHDs as its classification accuracy is very high. In the next part of the thesis we will develop a SHD using EMG as a source of getting input signals from the user.

Chapter 4

Underactuated prosthetic hand for grasping common objects

Grasping objects is an essential part of daily life, and it can be challenging for individuals with upper limb motor disabilities. Quadriplegic subjects face significant challenges in performing activities of daily living (ADLs) due to the loss of hand function, which severely affects their independence, social participation, and quality of life [1]. The use of prosthetic hands can greatly improve their quality of life, but traditional prosthetic hands with rigid fingers lack the dexterity to grasp different types of objects.

In recent years, researchers have been exploring underactuated prosthetic hands as a solution to this problem. Underactuated prosthetic hands have fewer degrees of freedom than traditional prosthetic hands, but they can grasp a wider variety of objects due to their compliance and adaptability [2]. These hands can be controlled using simple input signals and can adapt to the shape of the object being grasped without requiring complex algorithms.

The development of underactuated prosthetic hands for quadriplegic subjects is an active area of research, and there have been significant advancements in recent years. In the published literature, researchers have proposed various approaches to design underactuated prosthetic hands for grasping common objects. Some researchers have focused on developing prosthetic hands with a limited number of grasping modes, such as the five grasp poses of cylindrical, tip, hook, lateral, and palmar grasp [3]. Other researchers have explored using machine learning algorithms to enable the prosthetic hand to learn how to grasp objects [4].

A literature review of recent research papers on the development of underactuated prosthetic hands reveals that a significant number of researchers have focused on the design of hands that can grasp common objects with few degrees of freedom. For instance, Matthies et al. [1] designed a three-fingered underactuated prosthetic hand that could grasp cylindrical, spherical, and flat objects with different diameters. The hand utilized an underactuated mechanism with only two actuators, allowing it to adapt to the shape and size of the object being grasped. The authors reported that their design was successful in grasping the targeted objects.

Another interesting design was proposed by Fishel et al. [2], who developed a six-fingered underactuated prosthetic hand for grasping irregularly shaped objects. The hand utilized a mechanism of four actuators that could control the opening and closing of all fingers simultaneously. The authors conducted experiments to evaluate the hand's performance in grasping irregularly shaped objects, and the results showed that the hand was able to grasp the objects effectively.

Moreover, Cho et al. [3] developed a five-fingered underactuated prosthetic hand that could grasp different shapes and sizes of objects. The hand utilized a mechanism of three actuators that could control the fingers' opening and closing. The authors conducted experiments to evaluate the hand's performance in grasping various objects and found that the hand was successful in grasping the objects.

In recent years, there has been a growing interest in the use of electromyography (EMG) signals to control underactuated prosthetic hands. EMG signals are generated by the muscles during voluntary movements and can be used to predict the intended movement of the user. A study conducted by Amsüss et al. [4] used EMG signals to control an underactuated prosthetic hand for grasping different objects. The authors reported that the hand could successfully grasp various objects with different shapes and sizes.

While EMG signals have shown promising results in controlling underactuated prosthetic hands, other studies have explored the use of electroencephalography (EEG) signals for controlling prosthetic hands. EEG signals are generated by the brain and can be used to predict the intended movement of the user. A study conducted by Li et al. [5] used EEG signals to control a prosthetic hand for grasping different objects. The authors reported that the hand could successfully grasp various objects with different shapes and sizes.

However, there are some limitations associated with using EEG signals for controlling prosthetic hands, such as low signal-to-noise ratio, which affects the accuracy of the control. Moreover, the use of EEG signals requires a more complex signal processing algorithm than EMG signals.

One study by Dollar and Howe (2006) proposed a new approach for designing underactuated hands using a dynamic model to optimize grasp stability. The authors focused on creating hands with multiple degrees of freedom and demonstrated their feasibility through simulations. However, their approach required complex and expensive hardware, which may not be practical for many users.

Another study by Jiang et al. (2014) developed an underactuated prosthetic hand using shape memory alloy wires as actuators. The authors demonstrated that their hand was capable of performing a variety of grasping tasks, including grasping of cylindrical objects and key pinch grasping. However, their approach required precise control of the shape memory alloy wires, which may be difficult to achieve in practical applications.

The methodology in the present work utilizes EMG signals recorded during eye blinks to operate the underactuated hand. This approach has several advantages over previous work. Firstly, it does not require complex or expensive hardware, making it more accessible to a wider range of users. Secondly, it can be easily integrated with existing assistive devices, such as wheelchairs or communication devices, allowing for a more seamless user experience. Additionally, our approach utilizes a natural and intuitive input method, which may be preferred by users over more complex input methods used in previous work.

Overall, the literature on underactuated prosthetic hands demonstrates the potential for these devices to improve the quality of life for individuals with disabilities. Our methodology builds upon this previous work by utilizing a novel input method that is intuitive, accessible, and can be easily integrated with existing assistive devices.

This chapter focuses on the development of underactuated prosthetic hands for quadriplegic subjects.

4.1 Methodology:

Selecting an appropriate grasp for an object is a challenging task as there are many possibilities. However, humans tend to simplify this problem by choosing a suitable grasping pose for a group of objects. One approach to achieving this is by modeling objects as a set of primitive shapes such as cylinders, spheres, and cones, and then deciding the starting pose of the hand based on the shape of the object to be grasped. According to a study by Eppner et al. (2020), this approach has been shown to be effective in grasping various objects.

Moreover, it has been established from the literature that five grasp poses, including cylindrical, tip, hook, lateral, and palmar grasp, can be used to grasp a vast range of objects if the hand has underactuated fingers. The underactuated fingers allow for flexible finger movements that are necessary to achieve stable grasps for different objects. A study by Ma and colleagues (2018) evaluated the effectiveness of these grasp types in object grasping and found that they were successful in grasping a wide range of objects.

Another important factor to consider when selecting a grasp pose is the object's size and shape. For instance, small objects such as pens or coins require a different grasp pose than larger objects such as cups or plates. According to a study by Ciocarlie et al. (2009), robotic grippers need to adjust their grasping parameters based on the object's size and shape to achieve optimal grasping. Similarly, human hands adjust their grasp according to the object's size, shape, and weight. Recent advances in robotic technology have made it possible to achieve underactuated fingers in robotic hands. Underactuated fingers allow the robotic hand to adapt to the shape of the object being grasped and reduce the complexity of the grasping process. This technology has made it possible for robotic systems to grasp a wide range of objects with greater efficiency and success rates.

4.2 Mechanism of collecting control signals from users

However, distinguishing between involuntary and voluntary eye blinks has been a challenge due to the frequency of blinks in humans. This raises the question of how to differentiate between the two types of blinks when designing a self-help device based on eye blinks.

It has been discovered that the mechanism of voluntary blinking and involuntary blinking is fundamentally distinct. Human motor components can be classified into two parts: the visceral motor system, which controls involuntary muscle movements, and the somatic motor system, which controls voluntary muscle movements. Therefore, voluntary blinks can be detected separately by measuring the electromyography (EMG) signal from the appropriate muscle. The orbital part of the orbicular oculi muscle is considered the optimal candidate for measuring voluntary blinks, as it is responsible for voluntary closure of the eyelids. The process of blinking occurs when the eyelid opens and closes, which is controlled by several muscles, including the Levator palpebrae superioris muscle, Muller's muscle, Frontalis muscle, and Orbicularis oculi muscle.

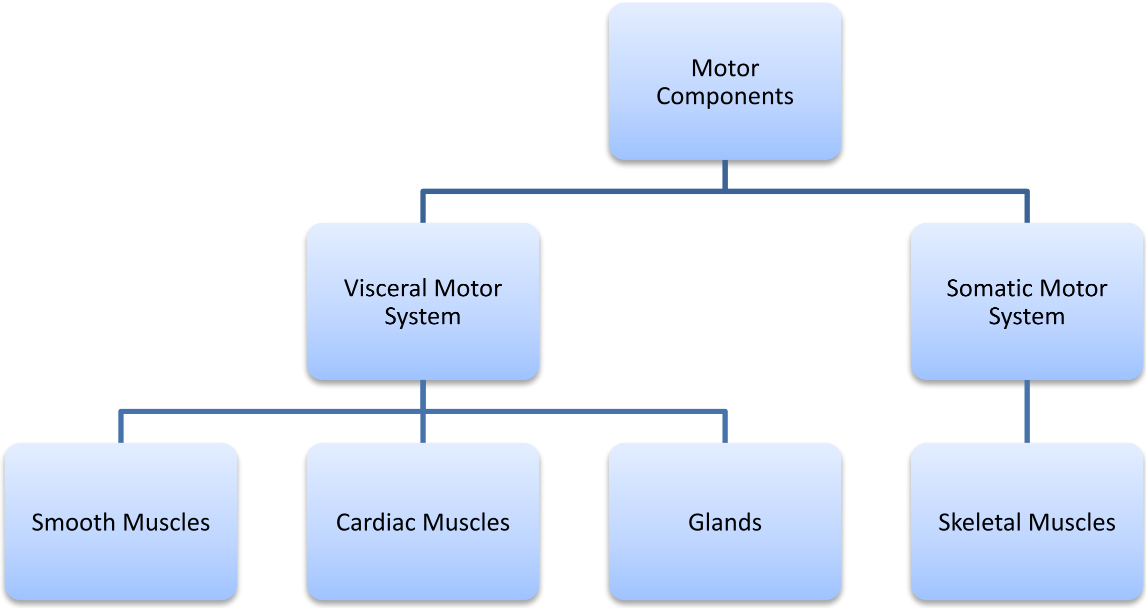


Figure 23: Motor Components

To understand how to distinguish between voluntary and involuntary blinks, it is important to understand the muscles responsible for eyelid movement. The Levator palpebrae superioris muscle is the primary muscle responsible for opening the eyelid, with minor contributions from the muller's muscle and frontalis muscle. On the other hand, the orbicularis oculi muscle is responsible for closing the eyelid. This muscle has two parts: the Orbital part and the Palpebral part. The Orbital part is responsible for voluntary closure of the eyelid, while the Palpebral part is responsible for involuntary closure. In the present study, electrodes were placed on the Orbital part of the Orbicularis oculi muscle to record EMG during voluntary closure of the eyelid using eyeblinks.

4.3 Grasping Mechanism

Choosing the optimal grasp for a given object is a complex task due to the vast number of possible grasp configurations. However, humans simplify this task by selecting appropriate grasping poses for groups of objects. They model objects as a set of primitive shapes, such as cylinders, spheres, cones, and boxes, and decide on the starting pose of the hand based on the shape of the object to be grasped. Through published literature, it has been well established that underactuated prosthetic hands can utilize five grasp poses, namely cylindrical, tip, hook, lateral, and palmar grasps, to grasp a vast range of objects. These grasp shapes are illustrated in Figure 24.

Figure 24: Cylindrical, Palmar, Tip, Lateral and hook Grasp

4.4 Finger Mechanism

In our study, we developed an underactuated mechanism that can preshape the finger as per the natural motion of the human finger. The finger contains 3 phalanges (Proximal, middle and distal). Proximal and middle phalanx is actuated with the help of 2 cross four bar chain mechanisms, while the distal phalanx is made up of a static arrangement of 3 links. The finger is actuated by only a single input.

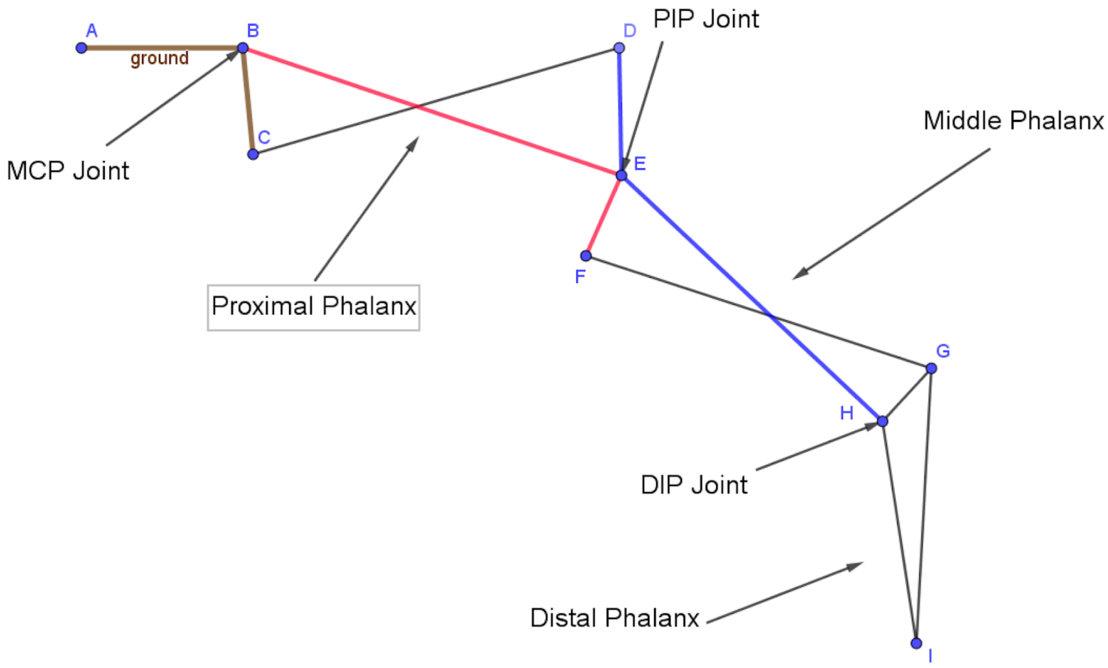


Figure 25 - Mechanism of proposed Underactuated Finger

The function of this finger is to mimic the natural motion of the human finger. All the joints of human fingers move simultaneously. They scarcely make individual movements. In this design too, all the joints move simultaneously to mimic the natural motion of the human finger. As shown in the figure the proximal phalanx rotates on MCP joint 'B' with the help of power generated from the actuator. Cross four-bar chain BCDE acts as a proximal phalanx. The motion from the proximal phalanx gets transferred to the middle phalanx (cross four-bar chain EFGH) as link DE is fixed to EH. Link EF is also fixed to BE. The Distal Phalanx GHI is a rigid structure with no motion between the links. The distal phalanx moves as the link GH moves. Figures 7a and 7b shows the locus of point I and the natural motion of the underactuated finger.

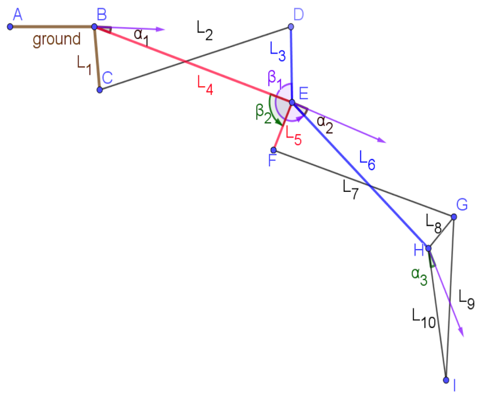


Figure 26a Figure 26a shows different links and angles of prosthetic finger.

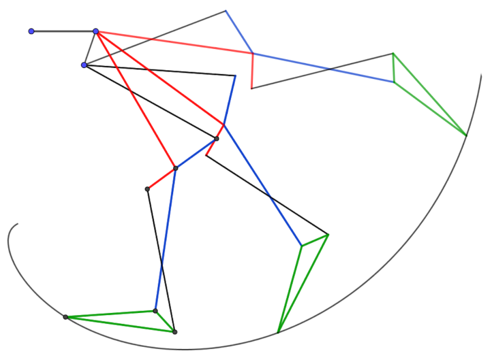


Figure 26b - Grasping space and motion of different links and joints during grasping.

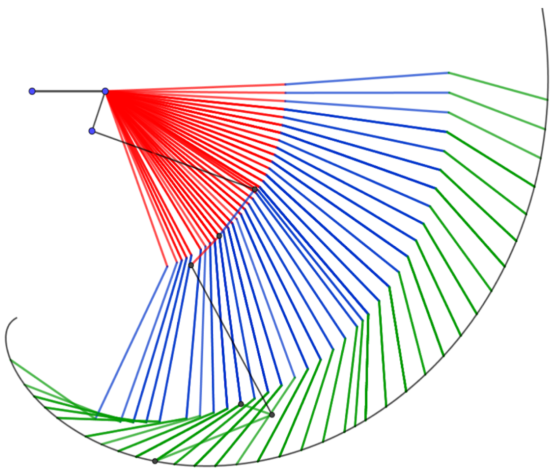


Figure 26c- Grasping space and motion of different links and joints during grasping.

This finger makes grasping tasks very easy as we need not consider the position of the phalanx. If we choose the right grasp preshape we can grasp the object effectively. As we aim to provide self-help devices for quadriplegic subjects, we have made our device in such a way that it does not require lots of control commands from the subject. They are required to choose the grasp preshape only. Once the preshape is chosen the underactuated hand works on its own to provide the grasp. We have used voluntary eye blinks to get control commands from the subjects.

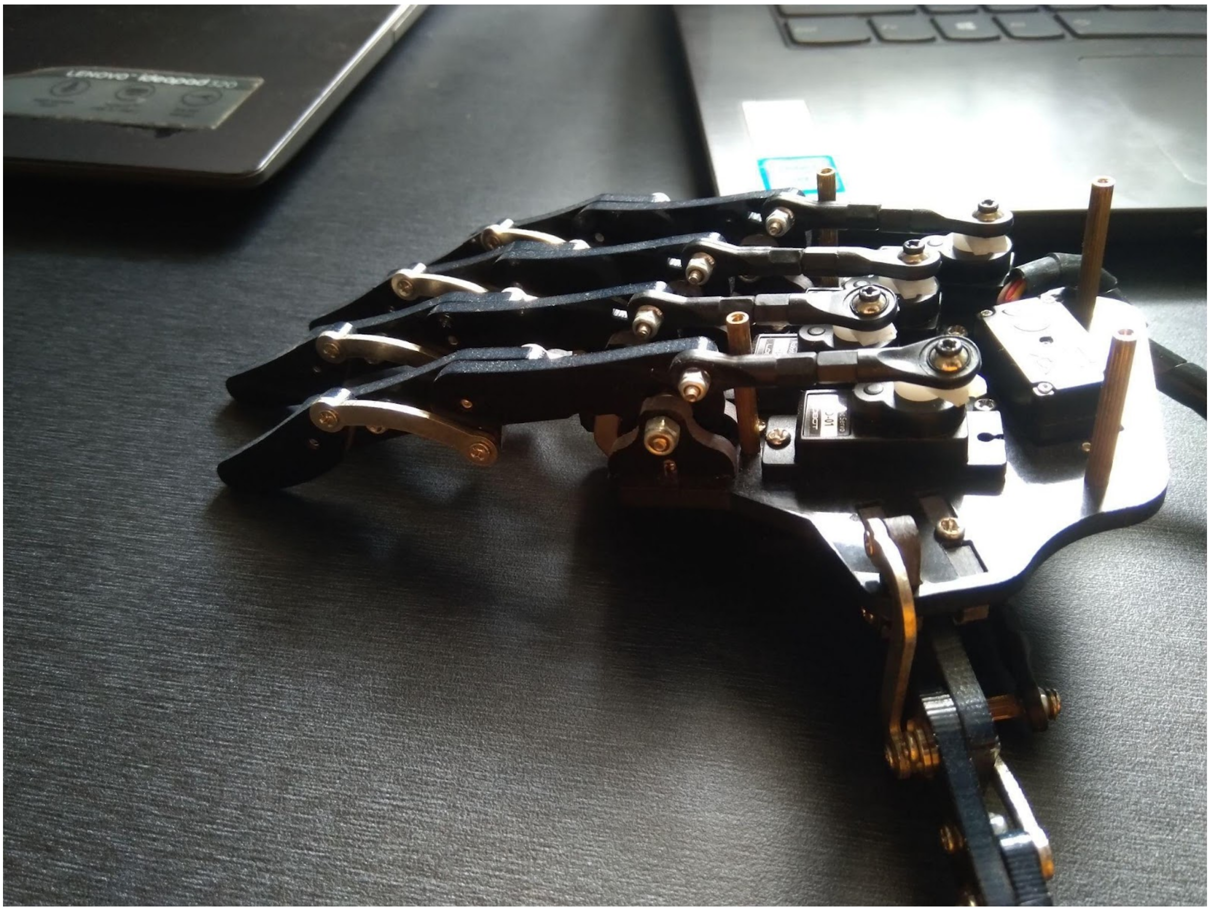


Figure 27- Underactuated Prosthetic Hand

4.5 Dataset:

Emg data was recorded from the orbital part of orbicularis occilli muscle of five health voluteers by the help of RMS Salus 2c EMG Machine. The aim was to identify the voluntary eye blinks. The recordings were performed twice daily over two consecutive days, with each recording session lasting from 9:00 am to 5:30 pm and consisting of three sessions, spaced 4 hours apart. The RMS Salus 2C EMG machine, provided by RECORDERS & MEDICARE SYSTEMS PVT. LTD. in India, was used to capture the surface EMG signals, and the RMS EMG Salus 2C V.7.7.1 software was used for recording.

4.6 Grasping Process

Following strategy was followed to perform the grasping operation

Step 1. The subjects were asked to view a computer screen where images of different hand configurations were flashed in a loop.

Step 2. Subjects were asked to blink voluntarily whenever the image of their choice was flashed.

Step 3. Whenever a blink was detected an audio message was played asking if you wanted to do the selected grasp.

Step 4. The subject was again asked to confirm by blinking, if blink was detected wrongly then the subject was asked to do nothing.

Step 5. If the subject confirms the grasp selection then commands were sent to the actuator.

Step 6. If no grasp was detected till the end of the loop then the loop was re-initiated.

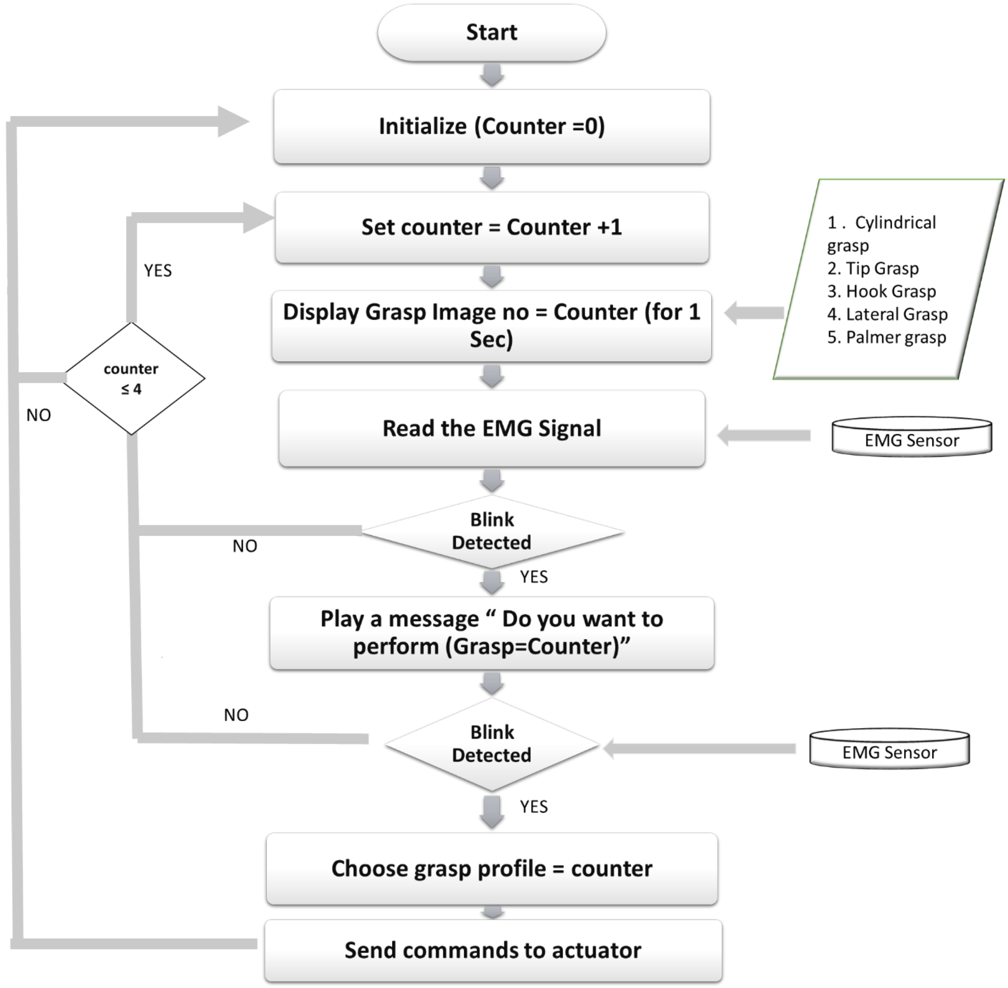


Figure 28- Following flowchart shows in details the algorithm of grasping

The most important step in this process is the detection of the eyeblink. We have already demonstrated in the previous chapter that eyeblinks can be easily detected from a recorded dataset. We used four different machine learning techniques and each technique gave very good classification accuracy. For the detection of eyeblinks from this live recording also, we followed the previously used pre-processing technique of taking segments of 1 sec. The aim was to detect if a blink was detected during the sec or not. Based on if the blink was detected or not detected, the next section of the algorithm was implemented.

The other pre-processing techniques used in chapter 3 of filtering , converting negative data points to positive, exponential smoothing, and normalizing were also used in the process of blink detection.

Once the data was pre-processed, two conditions were checked, i) if the amplitude is higher than the threshold amplitude ii) if the slope is higher than the threshold slope. If both the conditions were satisfied then it was considered that the blink was performed correctly. The threshold amplitude and threshold slope were obtained from the initial recording done during the resting phase.

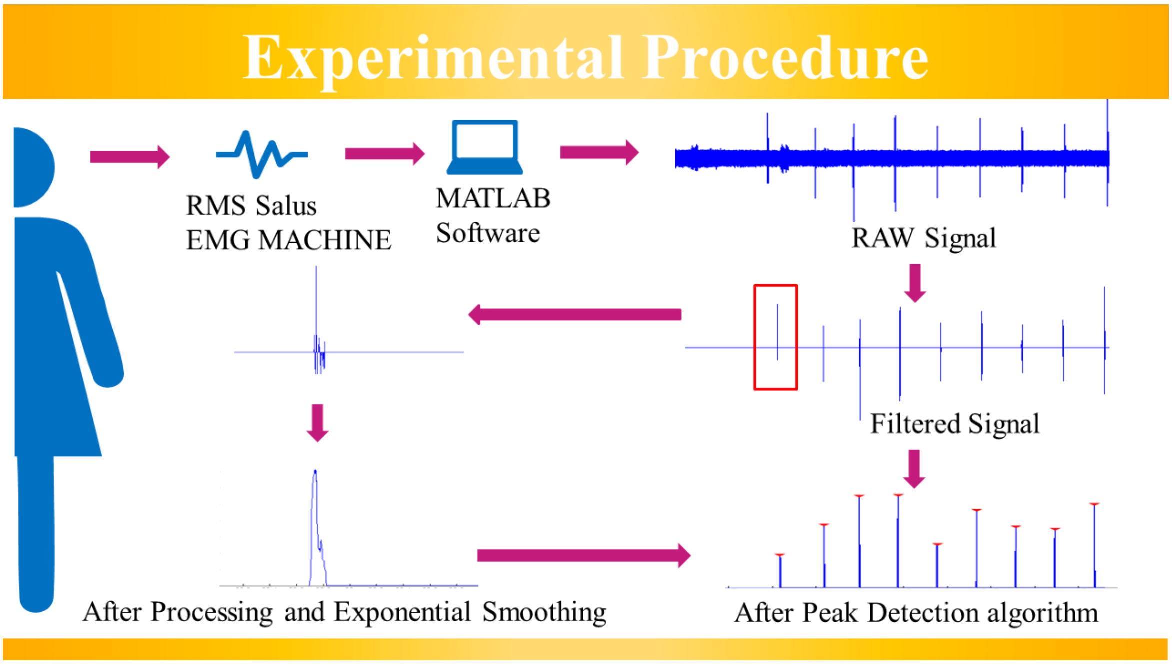


Figure 30: Experimental procedure

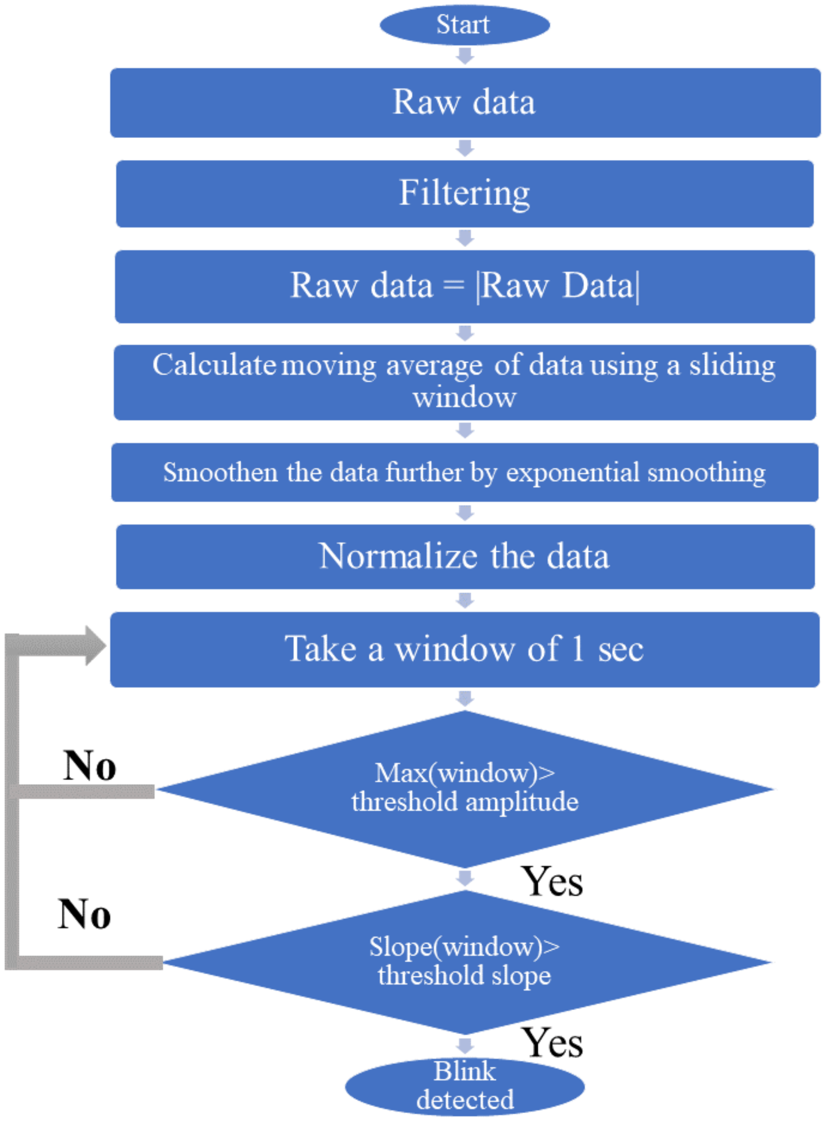


Figure 29: Blink detection algorithm

4.7 User Experience

A survey was designed to evaluate the usability and user experience of a device that uses a novel Grasping Algorithm, likely for the purpose of assisting individuals with disabilities, such as quadriplegia. The survey consists of ten statements or questions, with respondents rating their agreement or disagreement on a Likert scale.

The results of this survey can provide valuable insights into how users perceive the device and the novel Grasping Algorithm, as well as their overall satisfaction with the device's performance. Positive responses to statements such as "I found the device to be comfortable" and "It was easy to grasp objects using the novel Grasping Algorithm" suggest that users may be more likely to continue using the device and achieve their intended goals. Conversely, negative responses or lower agreement with certain statements could indicate areas for improvement or potential barriers to adoption.

In addition to assessing user satisfaction, this survey can also identify potential areas for future development or research. For example, if respondents consistently rate the voice feedback as unhelpful or difficult to understand, designers may consider alternative methods of providing feedback, such as visual cues or haptic feedback.

Overall, conducting a survey such as this can help developers and researchers understand user needs and preferences, as well as identify areas for improvement or refinement. This can ultimately lead to more effective and user-friendly devices that can improve the lives of individuals with disabilities.

4.7.1 Results of the survey

The survey results indicate that users generally had a positive experience with the device and the novel Grasping Algorithm. The mean response for most statements falls between 3.6 and 4.8 on a scale of 1 to 5, indicating that most users agreed or strongly agreed with the statements.

In particular, respondents found the Grasping Algorithm to be stable (mean of 4.8) and easy to use (mean of 3.8). Additionally, most users would recommend the device to quadriplegic individuals (mean of 4.6). These results suggest that the device and algorithm have the potential to be effective tools for assisting individuals with disabilities.

Respondents also found the GUI to be visually appealing (mean of 4.6) and the voice feedback to be helpful (mean of 4.8). These positive responses indicate that the device's user interface and feedback mechanisms were well-designed and effective.

However, respondents were less enthusiastic about the device exceeding their expectations (mean of 3.2), suggesting that some users may have had higher expectations for the device's performance or features. Additionally, while respondents found the device comfortable (mean of 3.6), there was a relatively high standard deviation of 0.55, indicating that some users may have had different experiences or preferences for comfort.

Overall, the survey results suggest that the device and novel Grasping Algorithm have the potential to be effective tools for individuals with disabilities. However, designers may want to focus on improving the comfort of the device and managing user expectations to maximize user satisfaction.

	Mean	Standard Deviation
I found the device to be comfortable	3.6	0.53
I found the Noval Grasping Algorithm to be stable	4.8	0.4
It was easy to grasp objects using the novel Grasping Algorithm	3.8	0.83
I would recommend this device to a quadriplegic person	4.6	0.89
The device has exceeded my expectations	3.2	0.45
The GUI was Visually appealing	4.6	0.55
It was easy to follow all the instructions	4	0.11
Practicing daily will help me use the device more efficiently	5	0
The voice feedback was helpful	4.8	0.45
Overall Experience	4.6	0.55

Table 2 : Results of User Satisfaction Survey

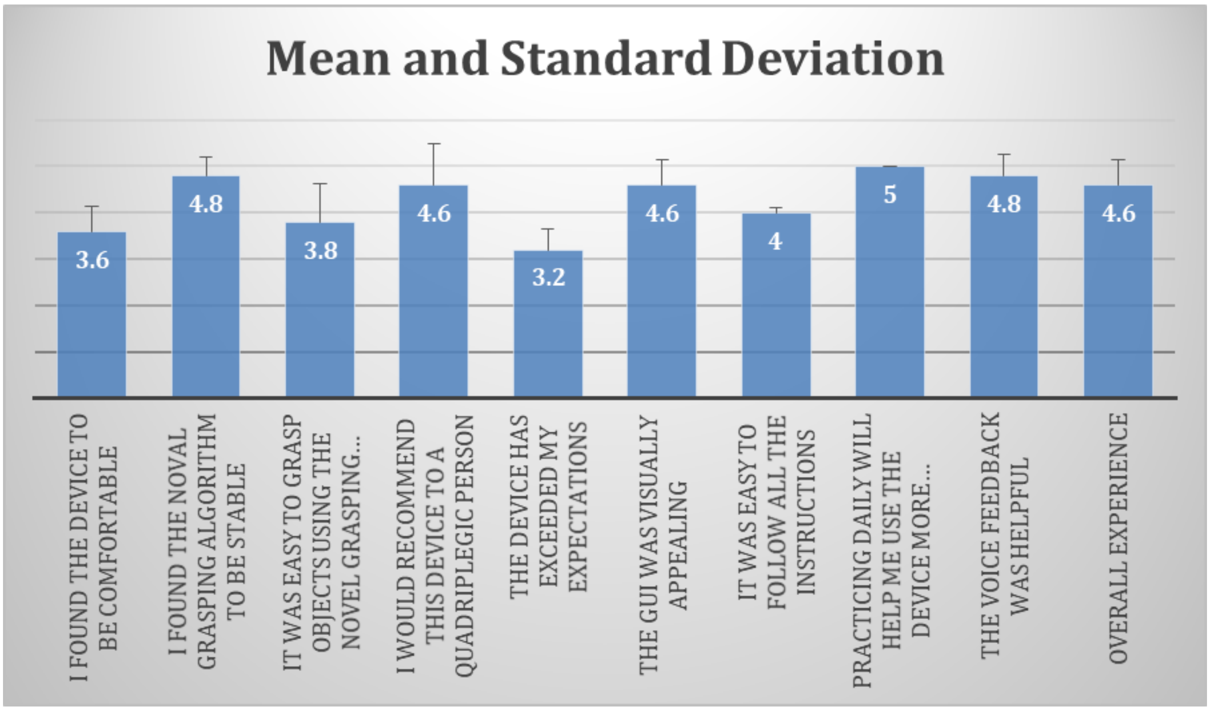


Figure 31- Mean and Standard Deviation of Results

Chapter 5

Aluminum based Low Cost Composite Material for Developing Prosthetics

5.1 Introduction

Currently, over one billion individuals worldwide are experiencing some form of disability, a number that is rapidly increasing. However, in cases where healthcare services for disabled individuals are available, they are often under-resourced or of poor quality [109]. Consequently, there is an urgent need to expand disability services in primary healthcare, particularly in the area of rehabilitation interventions. The most recent census in India revealed that out of a total population of 121 million, approximately 27 million people have some form of disability, accounting for 2.21% of the total population. A majority of these disabled individuals (69%) reside in rural areas [110]. Specifically, 18.6 million individuals are from rural areas while 8.1 million reside in urban areas. Within India, movement disabilities affect 20% of disabled individuals, with the highest number of disabilities occurring within the age group of 10-19 years [111]. Those with disabilities experience numerous constraints, including the inability to afford assistive devices, particularly in low and middle-income countries [112] [113]. Studies have shown that nearly 50% of individuals with disabilities cannot afford basic healthcare services [114].

In addition to cost, there are other important characteristics to consider when designing an upper limb prosthetic device, such as weight, strength, corrosion resistance, and customization [117]. Traditional manufacturing techniques for these devices, such as 3-D printing and injection molding, have limitations. While 3D printing can create customized devices, they often lack strength and are prone to wear and tear [117]. Injection molding can produce devices with adequate strength, but customization is difficult and the initial cost is high [117]. The use of lighter materials, such as aluminum, is a common practice in prosthetic device manufacturing, as it reduces weight and allows for customization. However, lighter materials often lack strength, toughness, and rigidity, with lower yield strength [117]. Composite materials, which are produced by mixing two or more materials, have shown promise in overcoming these limitations. The use of composite materials in prosthetic devices can provide superior mechanical properties compared to weight and high resistance to corrosion, particularly when made with aluminum [108-110]. In order to produce the best blend of properties at a lower cost, it is crucial to choose the appropriate fraction of volume, geometry, and type of reinforcement [111]. However, in the molten metal matrix, the low wettability of ceramic particles can make conventional casting of Metal Matrix Composites (MMCs) difficult [112-114]. A powder metallurgy technique called mechanical milling can help disperse hard particles homogeneously and defragment ceramic clusters, allowing for greater control over the size of the particle [112-114].

If any of the constituent phases of a composite have at least one dimension less than 100 nm, it is called a nanocomposite. An important class of nanomaterials are 1-D nanostructures. These materials are the basic building blocks for building composites in the field of nanotechnology.

Carbon nanotubes were discovered in 1991 by a scientist named Iijima. Carbon nanotubes have very high tensile strength ($150 * 10^3$ MPa) and stiffness ($1 * 10^6$ MPa). It also has a very high thermal conductivity ($3000 - 6000\frac{W}{mK}$)[108]. All these properties have made carbon nanotubes a very important element, opening up endless possibilities in the field of materials science. The researcher uses them as reinforcing materials in his MMC, PMC and CMC type composites. The most common methods of reinforcing carbon nanotubes to fabricate composites are powder metallurgy, fusion, thermal spraying, and electrochemical methods.

Mololithic boron carbide (B4C) is also a very good candidate for use as a reinforcement in aluminum composites. On the one hand it has a low density (2.52 gcm3) and on the other hand it has a very high hardness, almost the same as diamond (9.5+ on the Mohs scale). It is thermally stable, chemically inert, abrasive, and has properties such as wettability.

The inherent brittleness of monolithic boron carbide limits its use. It is recommended for use as an additive or reinforcing agent for other metals. This will eliminate any problems associated with it.

In this study, we focused on the dispersion of boron carbide particles in aluminum composites. This is very important regarding the use of boron carbide in structural applications. Being very hard, it has great potential to improve the mechanical performance of other metals. If these particles can be uniformly dispersed in the aluminum matrix using a solid state method, the mechanical properties of the alloy will be improved.

Uniform distribution of boron carbide or carbon nanotubes in the aluminum matrix is a major challenge. Strategic selection of techniques for this process is therefore very important. A systematic literature search was performed to gain insight into which techniques are used in the recent literature.

Kuzumaki et al. [3] began using carbon his nanotubes as reinforcements for MMCs. They used an aluminum matrix to strengthen the carbon nanotubes inside. Currently, carbon nanotubes are reinforced with various types of materials such as Cu, MG, Ti and NI.

However, the use of carbon nanotubes has limitations. Carbon nanotubes form bundles due to strong van der Waals forces. Techniques such as ball milling, chemical vapor deposition, mechanical forcing, and carbon nanotube growth on metal are used to achieve uniform distribution.

Esawi and Mursi [111] experimentally investigated whether carbon nanotubes can be homogeneously dispersed in an Al stream by mechanical permission. In this study, carbon nanotubes were ground in a ball mill at a speed of 200 rpm for 47 hours. After that, when the growth of carbon nanotubes was examined by FESEM, it was found that the carbon nanotubes were uniformly distributed and did not damage the structure.

Another study [113] used a new method to disperse carbon nanotubes in aluminum powder uniformly. In this study, methane/argon gas was used in his CVD reactor. Carbon nanotubes were grown on Al particles. This resulted in a uniform distribution of carbon nanotubes.

A published study by Cha et al. [115]. Carbon nanotubes were dispersed in the Cu matrix by mixing at the molecular level. In this method, a salt containing Cu ions was placed in the carbon nanotube suspension. The solution was then dried in a temperature range of 212-482°F. Finally, the powder was calcined and reduced in a hydrogen atmosphere. TEM studies revealed a uniform distribution of carbon nanotubes. A thorough literature review reveals that powder metallurgy (PM) is the most suitable and most commonly used method for nanocomposite fabrication. Another finding from a thorough review of the literature is that mechanical permitting is the most appropriate technique when carbon nanotubes and his B4C must be evenly dispersed in an Al matrix.

The results of the above literature search form the basis of our study. In this study, we investigated how milling time affects the anatomy of B4C and carbon nanotube-reinforced aluminum matrix composites. It study is relevant because it will give a direction to develop low-cost prosthetic devices with the help of a novel material.

5.2 Methodology

For this study Al, B_4C and carbon nanotubes were used as a raw material. Firstly half gram of carban nano tubes were mixed in 0.2L ethanol. 2.5 g of Boron carbide was added to this solution. Then the powder obtained was sonicated for half an hour. The sonicated powder was then dried in a vacuum oven at a temperature of 140° F for 2 hours.

Once dry powder was obtained, it was processed using a ball mill. Four different milling times (1, 2, 4, 8 hours) were used so that effect on the milling time of the Nanocomposite powder can be studied. The speed of rotation of the ball mill was kept constant at 200 rounds per minute. Powder to ball ratio was also kept constant at 1:6. In order to avoid the cold welding of Al, ethanol was added as a process control agent.

The resultant from the above experiment was studied in a scanning electron microscope in order to determine the spread of both reinforcements in the aluminum matrix.

5.3 Results and Discussion

Ball mills use centrifugal force to collide powder with balls. These collisions cause severe plastic deformation (SPD) of the powder. These collisions not only cause powder crushing and cold welding. The strength of SPD or cold welding depends on the milling speed, milling time and process control measures used.

5.3.1 Milling of Al Powder for different time intervals

Firstly milling was done on Al powder alone without mixing reinforcements. The resultant powder was studied under Scanning electron microscope.

Fig. 32, shows Scanning electron microscope image of Al powder after milling for a) 1 hour, b) 2 hour, c) 4 hour, d) 8 hour

After 1 h of milling, the initially irregularly shaped Al powder changed into a flaky shape due to strong plastic deformation. A powder yield of about 9-10% is reported in the literature because the process control agent Al powder used adheres to both the walls and the balls of the ball mill. A process control agent (1.5% ethanol) helped to effectively control the cold welding of Al particles. This occurs because the process control agent ethanol spreads throughout the mixture and coats the Al particles as soon as the ball mill starts. As a result, the particles do not come into direct contact with either the stainless steel walls or the balls of the ball mill. This helps prevent galling.

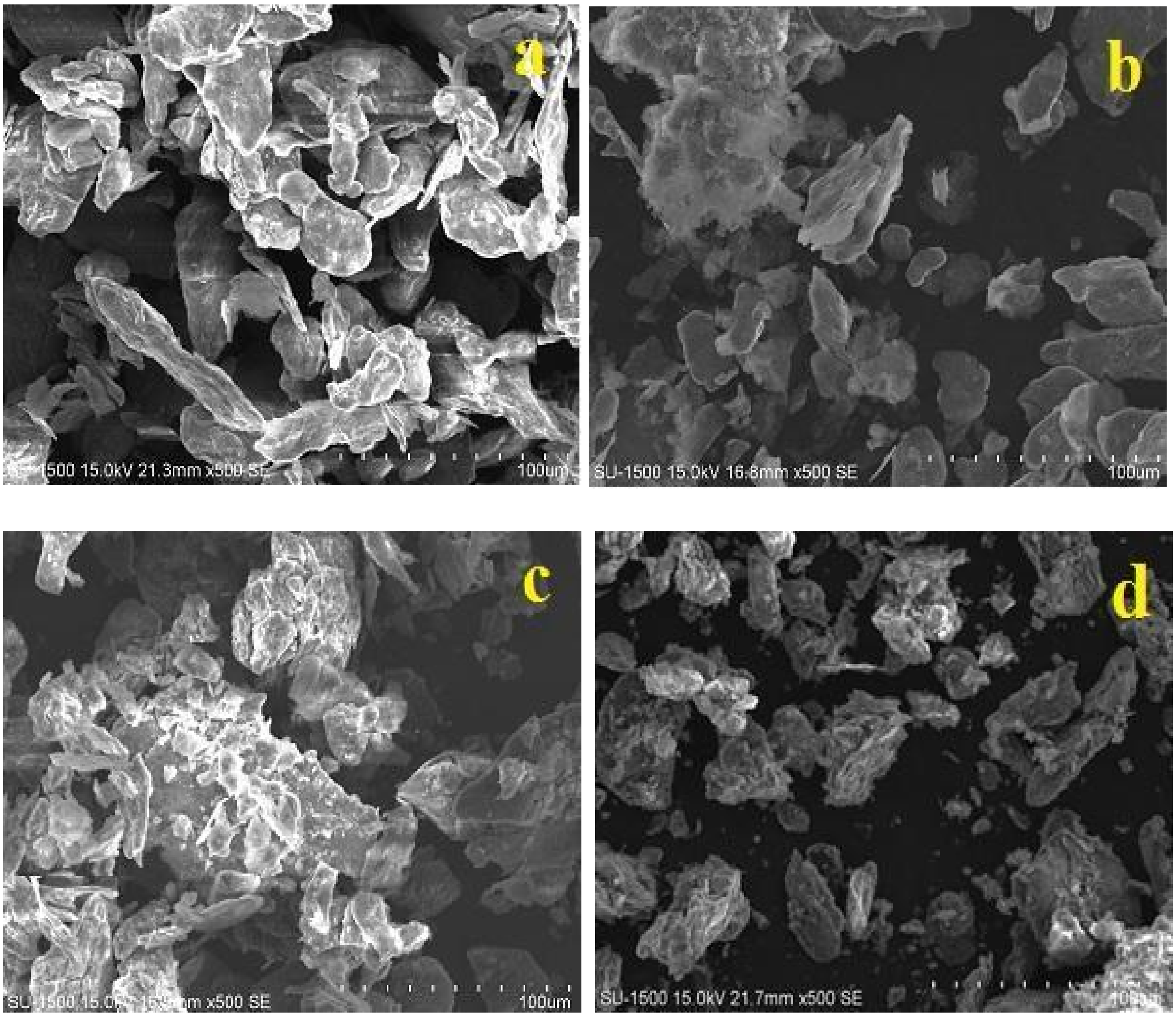


Figure 32: Scanning electron microscope image of Al powder after milling for a) 1 hour, b) 2 hour, c) 4 hour, d) 8 hour

As can be seen from Fig. 32a, the structure of Al after ball milling for 1 h was flaky in nature. This scaly structure was still present after 2 hours of grinding. After 4 hours of milling, this flaky structure started to crack as the balls continuously collided with the flaky Al particles. This can be seen in Figure 32c. After 8 hours of milling, almost all of the flaky particles were broken, but the resulting small particles began to cold weld. Note that cold welding and grain breakage reach equilibrium as milling time increases.

5.3.2 Milling of nanocomposite Powder for different time intervals

In order to make a Nanocomposite with homogeneous properties the even spread of both the reinforcements i.e Carbon nanotubes and boron carbide is required in the Al matrix. This was achieved with the help of the experiment mentioned in Materials and Method. The nanocomposite powder obtained was milled for different time intervals i.e. (a) 1 hour, (b) 2 hours, (c) 4 hours, and (d) 8 hours.

Initially, the aluminum particles began to transform into flake-like structures, while the boron carbide remained unchanged and remained polygonal during his first hour of milling. Boron carbide particles, indicated by arrows, can be seen embedded in the aluminum flakes in Figure 33a.

After 2 h of grinding, it was observed that the flaky Al particles began to break up. This Al grain fracture occurred much earlier than in monolithic aluminum. The reason was the boron carbide particles. Since boron carbide is a hard ceramic, it causes localized plastic deformation. This increases the work hardening of aluminum. When this work hardening exceeds a threshold, the Al begins to crack. Boron carbide, therefore, acts as a grinding aid. This phenomenon can be seen in Figure 33b.

At the initial stage of milling, carbon nanotubes, and boron carbide reinforcement adhered to the Al matrix. However, as the milling time increased, both reinforcements began penetrating the base metal due to cold welding. This made it easier for cracks to spread. Crack propagation led to fractures.

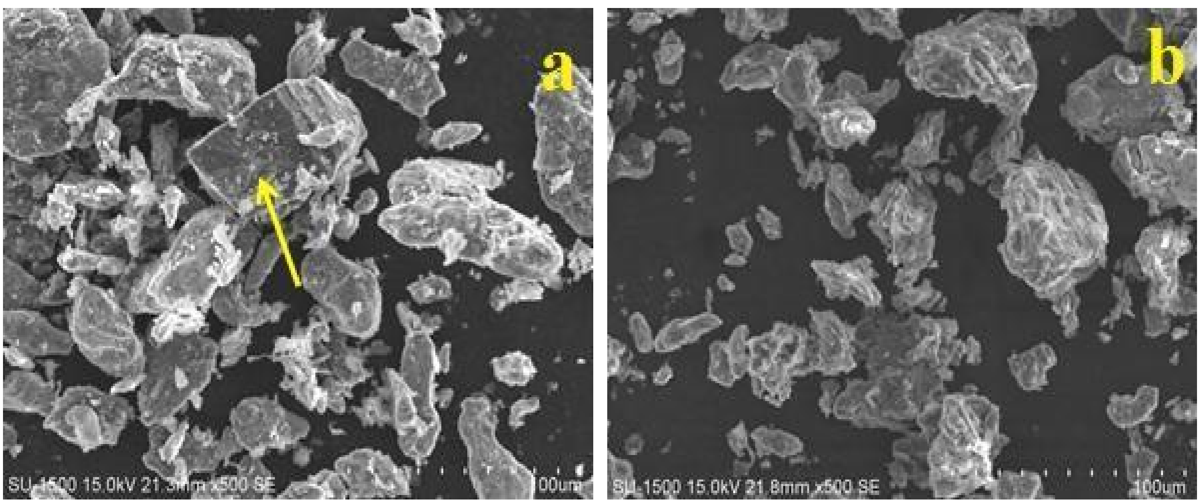
The fracture surfaces where the boron carbide and carbon nanotubes penetrate the matrix are cold welded again and the cycle continues. This allows all stiffeners to penetrate evenly into the Al matrix. After 4 hours of milling, it was observed that the reinforcement was spread evenly within the matrix without any defects in the reinforcement, as seen in Fig. 33c.

Remarkably, there was no accumulation of reinforcements, indicating an even distribution. It is also worth noting that the particles started to become equiaxed at this point. Equilibrium is reached faster with nanocomposites than with Al alone. The reason was the presence of carbon nanotubes and boron carbide. Carbon nanotubes were found on the fracture surface. It can be seen in Figure 33c, as indicated by the arrow.

The addition of process control agents helped to avoid the clustering of enhancements. This accumulation has been reported in other studies [112], [115] in which no process control agents were used.

Carbon nanotubes and boron carbide were also found to reduce particle size, but other researchers reported that these enhancements played no role in influencing particle size. After 8 hours of milling, the powder began to exhibit an equiaxed structure. This indicates that sufficient milling time has been achieved and a balance between galling and crushing has been achieved.

It is worth noting that no reinforcing particles were present on the surface of the composite. This indicates that the reinforcement is built into the Al matrix. No free carbon nanotubes or boron carbide particles were found, indicating that boron carbide and carbon nanotubes are bound together within the Al matrix.



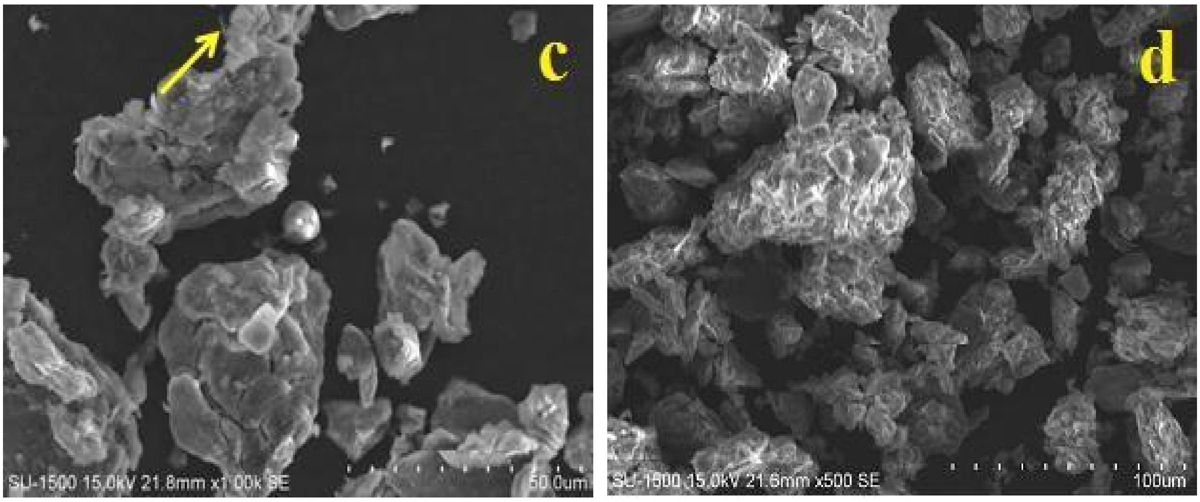


Figure 33: Scanning electron microscope image of nanocomposite after milling for (a) 1 hour, (b) 2 hours, (c) 4 hours, and (d) 8 hours.

5.4 Conclusion

In this study, we have used the above-mentioned findings of previous studies and investigated how milling duration affects the anatomy of an aluminum matrix composite material having B4C and carbon nanotubes as reinforcements.

we aim to develop a BMI-based rehabilitation system that can help individuals with disabilities to regain motor functions. The use of lightweight and high-strength nanocomposite materials can significantly improve the performance and functionality of the devices used in the rehabilitation process.

The results of our study suggest that ball milling and ultra-sonication techniques can be effectively used to enhance the mechanical properties of nanocomposite materials. This implies that the use of these techniques can help in developing lightweight and high-strength materials that can be utilized in the development of advanced prosthetic limbs and other devices for the rehabilitation of disabled individuals.

Furthermore, the use of ethanol as a PCA can significantly improve the dispersion of the reinforcements in the matrix, which can further enhance the mechanical properties of the resulting nanocomposite material. This can have significant implications in developing devices that are more durable and can withstand the wear and tear of daily use.

Future research in this area can focus on exploring the use of different PCAs to further enhance the dispersion of the reinforcements in the matrix.

In conclusion, The use of nanocomposite materials with enhanced mechanical properties can significantly improve the performance and functionality of the devices used in the rehabilitation process. Therefore, the results of this study can be utilized to develop advanced prosthetic limbs and devices that can help individuals with disabilities to regain motor functions and improve their quality of life.

Chapter 6

Conclusion and future works

In this study, we have focused to develop a Brain Machine Interface-based Self Help Device for extremely disabled people. Our study found that EEG-based BMI classification accuracy can be improved significantly when using a dataset without out-of-control events. However, it is challenging to use EEG outside the lab environment due to various factors such as movement artifacts, electrode placement, and signal interference from other sources.

Our investigation of the effectiveness of four machine-learning techniques for classifying EMG signals recorded during eyeblinks showed that EMG has great potential as an alternative method for developing self-help devices for quadriplegic individuals. Our study involved five healthy participants and was conducted over two consecutive days. The classification accuracy of EMG was found to be very high, and we developed a SHD using EMG as a source of input signals from the user.

After finalizing EMG to be the preferred method for developing SHD, we also developed a technique in which the orbicularis oculi muscle was used to generate control signals when the user performed voluntary blinks, for operating a self-help device. An underactuated prosthetic hand was also designed which was operated with the help of voluntary eyeblinks. The Prosthetic hand provided the ability to grasp objects of multiple shapes and sizes with only one control command, i.e. eyeblinks. A computer program was developed to help users orchestrate the grasp.

Furthermore, we explored ways to reduce the cost and enhance the mechanical properties of prosthetic hands by using a novel material. We used an aluminum matrix-based nanocomposite with boron carbide and carbon nanotubes as reinforcements. We studied how different speeds affect the even distribution of reinforcements and the role ethanol plays as a process control agent in the entire process. Our findings suggest that this new material has the potential to significantly enhance the mechanical properties of prosthetic hands, making them more accessible and effective for a wider range of individuals.

The implications of this thesis are significant for the field of rehabilitation for disabled individuals. The development of self-help devices using EEG and EMG signals has the potential to greatly improve the quality of life for individuals with paralysis or other physical disabilities. The use of these signals to control prosthetic limbs and other assistive devices offers a new level of independence and mobility for individuals who were previously limited in their abilities.

Additionally, the development of new materials, such as the aluminum matrix-based nanocomposite described in this thesis, has the potential to significantly enhance the mechanical properties of prosthetic hands and make them more accessible and effective for a wider range of individuals. This could lead to a greater number of individuals with physical disabilities being able to use prosthetic devices and experience increased independence and mobility.

Directions for future works

The research presented in this thesis provides a foundation for future studies aimed at improving the quality of life for quadriplegic individuals. The findings and contributions of this work suggest several potential areas for further research. Firstly, future studies could explore the use of high-density EEG systems to further improve the accuracy of BMI classification. Incorporating more channels of EEG data can provide a more comprehensive view of brain activity during the task and may improve classification accuracy. Secondly, future work could focus on exploring the use of different PCAs to further enhance the dispersion of the reinforcements in the matrix. Additionally, investigating the potential of incorporating other types of reinforcements, such as graphene and ceramic nanoparticles, can also be an interesting avenue for further research.

Future research could also explore the incorporation of object identification techniques to determine the shape and size of objects, which could then be used in conjunction with the blink-controlled underactuated prosthetic hand developed in this thesis. Additionally, using path-finding algorithms to reach the object and grasp it could further enhance the functionality of the prosthetic hand. This would allow for greater independence and quality of life for disabled individuals.

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1. Jafar, M. R., & Nagesh, D. S. (2021). Literature review on assistive devices available for quadriplegic people: Indian context. *Disability and Rehabilitation: Assistive Technology*, 1-13.

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2. Jafar, M. R. (2022). Electromyography data recorded from orbicularis oculi muscle during a novel grasping pilot study. *All Life*, *15*(1), 678-683.

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