

# Neuromuscular Control for Lower Limb Prosthesis



Author

A/O MUHAMMAD ADNAN KHALIL

00000238701

Supervisor

DR. MOHSIN ISLAM TIWANA

DEPARTMENT OF MECHATRONICS ENGINEERING  
COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING  
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY  
ISLAMABAD  
JULY, 2019

# Neuromuscular Control for Lower Limb Prosthesis

Author

A/O MUHAMMAD ADNAN KHALIL

00000238701

A thesis submitted in partial fulfillment of the requirements for the degree of  
MS Mechatronics Engineering

Thesis Supervisor:

DR. MOHSIN ISLAM TIWANA

Thesis Supervisor's Signature: \_\_\_\_\_

DEPARTMENT OF MECHATRONICS ENGINEERING  
COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING  
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY,  
ISLAMABAD  
JULY, 2019

## **Declaration**

I certify that this research work titled “*Neuromuscular Control for Lower Limb Prosthesis*” is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student

MUHAMMAD ADNAN KHALIL

00000238701

## **Language Correctness Certificate**

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

Signature of Student

MUHAMMAD ADNAN KHALIL

00000238701

Signature of Supervisor

## **Copyright Statement**

- Copyright in text of this thesis rests with the student author. Copies (by any process) either in full, or of extracts, may be made only in accordance with instructions given by the author and lodged in the Library of NUST College of E&ME. Details may be obtained by the Librarian. This page must form part of any such copies made. Further copies (by any process) may not be made without the permission (in writing) of the author.
- The ownership of any intellectual property rights which may be described in this thesis is vested in NUST College of E&ME, subject to any prior agreement to the contrary, and may not be made available for use by third parties without the written permission of the College of E&ME, which will prescribe the terms and conditions of any such agreement.
- Further information on the conditions under which disclosures and exploitation may take place is available from the Library of NUST College of E&ME, Rawalpindi.

## **Acknowledgements**

I am thankful to my Creator **ALLAH SUBHANA-WATALA** to have guided me throughout this work at every step and for every new thought which **YOU** setup in my mind to improve it. Indeed I could have done nothing without **YOUR** priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was **YOUR** will, so indeed none be worthy of praise but **YOU**.

I am profusely thankful to my beloved parents who raised me when I was not capable of walking and continued to support me throughout in every department of my life.

I would also like to express special thanks to my supervisor Dr. Mohsin Islam Tiwana for his help throughout my thesis and also for Biomedical Instrumentation course which he has taught me. I can safely say that I haven't learned any other engineering subject in such depth than the ones which he has taught.

I would also like to pay special thanks to Mr. Muneeb Hassan Raja for his tremendous support and cooperation. Each time I got stuck in something, he came up with the solution. Without his help I wouldn't have been able to complete my thesis. I appreciate his patience and guidance throughout the whole thesis.

I would also like to thank Dr. Umar Shahbaz Khan and Dr. Amir Hamza for being on my thesis guidance and evaluation committee and their kind guidance through every step of my thesis and degree. My special Thanks to Dr. Javaid Iqbal for his help. I am also thankful to Abdul Hanan for his support and cooperation.

Finally, I would like to express my gratitude to all the individuals who have rendered valuable assistance to my study.

*Dedicated to my exceptional parents and beloved spouse whose  
tremendous support and cooperation led me to this wonderful  
accomplishment*

## **Abstract**

Transtibial amputees come across various stress related issues. Gait cycle of these amputees vary from a healthy human being due to deviation in stresses primarily related to human ankle. Human ankle biomechanics provides a control platform to analyze these stresses. Deviation in human ankle angles, required torque and positive work done required in various phases of a gait cycle thus becomes a focal point for understanding. Passive ankle foot prosthesis doesn't provide required work done for the amputee during powered plantar flexion phase of gait cycle since the energy stored doesn't suffice for the desired outputs therefore a more viable option is the use of powered active ankle foot prosthesis. To design a robust control mechanism for this powered ankle foot prosthesis is of utmost importance since it ensures mimicking human ankle biomechanics of a healthy human being for an amputee as well. Input to this control mechanism rests in understanding the amputee's intent through neuromuscular EMG (Electromyography) signals. This research thus focuses on simulating a control system for powered ankle foot prosthesis along with neuromuscular control which will result in a natural gait cycle and reduction of metabolic cost of transport (COT) of a transtibial amputee.

**Key Words:** *Amputee, Gait Cycle, Intent, Metabolic Cost of Transport, Neuromuscular, Prosthesis, Transtibial.*



# Table of Contents

|   |     |
|---|-----|
| <b>Declaration.....</b>   | i   |
| <b>Language Correctness Certificate.....</b>  | ii  |
| <b>Copyright Statement.....</b>   | iii |
| <b>Acknowledgements.....</b>  | iv  |
| <b>Abstract.....</b>  | vi  |
| <b>Table of Contents.....</b>   | vii |
| <b>List of Figures.....</b>   | ix  |
| <b>List of Tables.....</b>  | x   |
| <b>CHAPTER 1: INTRODUCTION</b>  | 1   |
| 1.1 Background.....   | 1   |
| 1.2 Anatomical Planes.....  | 1   |
| 1.2.1 Anatomical Movements for Lower Limb.....  | 2   |
| 1.2.1.1 Sagittal Plane Movements.....   | 3   |
| 1.2.1.2 Other Foot Movements.....   | 3   |
| 1.3 Gait Cycle.....   | 5   |
| 1.3.1 Stance Phase.....   | 5   |
| 1.3.2 Swing Phase.....  | 6   |
| 1.4 Transtibial Prosthetics.....  | 6   |
| 1.5 Objective.....  | 9   |
| <b>CHAPTER 2: LITERATURE REVIEW</b>   | 11  |
| 2.1 Human Ankle Biomechanics.....   | 11  |
| 2.1.1 Parameters – Human Ankle Biomechanics.....  | 11  |
| 2.1.2 Gait Cycle Sub Division according to Ankle biomechanics.....                                | 12  |
| 2.1.2.1 Sub Phases of Stance Phase.....   | 13  |
| 2.1.2.2 Sub Phases of Swing Phase.....  | 15  |
| 2.2 Electromyogram (EMG).....   | 15  |
| 2.2.1 Skeletal Muscles.....   | 18  |
| 2.2.2 Lower Limb Skeletal Muscles for EMG Signal.....   | 19  |
| 2.3 Neuromuscular Control for Lower Limb Prosthesis.....  | 21  |
| 2.4 Summary.....  | 23  |
| <b>CHAPTER 3: SURFACE ELECTROMYOGRAPHY (SEMG) FOR LOWER LIMB PROSTHESIS NEUROMUSCULAR CONTROL</b> | 24  |
| 3.1 Surface Electromyography (SEMG).....  | 24  |
| 3.1.1 Factors Affecting SEMG Signal Acquisition.....  | 24  |
| 3.1.2 Inherent Noise.....   | 24  |
| 3.1.3 Motion Artifacts.....   | 25  |
| 3.1.4 Depth of the Muscle.....  | 25  |
| 3.1.5 Spacing of Electrode.....   | 26  |
| 3.2 Intent Based Neuromuscular Control.....   | 27  |
| 3.2.1 Synthetic EMG Data.....   | 27  |

## Table of Contents (cont)

|  |   |           |
|--|---|-----------|
| 3.2.2  | Real Time EMG Data Recording.....                       | 29        |
| 3.3  | Summary.....  | 32        |
| <b>CHAPTER 4: CONTROL SYSTEM FOR POWERED LOWER LIMB PROSTHESIS</b> |   | <b>33</b> |
| 4.1  | Introduction.....                                       | 33        |
| 4.1.1  | Prosthesis for Control System.....                      | 33        |
| 4.1.2  | Reference Trajectories for Control System.....          | 34        |
| 4.2  | Control System.....                                     | 34        |
| 4.2.1  | SIMULINK Model.....                                     | 35        |
| 4.2.1.1  | Trajectory Generation Block.....                        | 35        |
| 4.2.1.2  | Conversion Block.....                                   | 36        |
| 4.2.1.3  | Controller Block.....                                   | 38        |
| 4.2.1.4  | Output Block.....                                       | 41        |
| 4.3  | Summary.....  | 42        |
| <b>CHAPTER 5: RESULTS AND DISCUSSION</b>                           |   | <b>44</b> |
| 5.1  | Results – SIMULINK MATLAB.....                          | 44        |
| 5.1.1  | Initial Results for Ankle Angles during Gait Cycle..... | 45        |
| 5.1.2  | Final Results.....                                      | 47        |
| 5.2  | Discussion.....   | 49        |
| 5.3  | Summary.....  | 52        |
| <b>CHAPTER 6: CONCLUSION AND FUTURE WORK</b>                       |   | <b>53</b> |
| <b>APPENDIX A</b>  |   | <b>55</b> |
| <b>REFERENCES</b>  |   | <b>62</b> |

## List of Figures

|  |    |
|--|----|
| <b>Figure 1.1:</b> Common levels of lower limb amputations.....  | 2  |
| <b>Figure 1.2:</b> Anatomical Planes for human body’s description.....   | 3  |
| <b>Figure 1.3:</b> (a) Extension & Flexion (b) Plantar flexion & dorsiflexion (c) Inversion & Eversion.....                      | 4  |
| <b>Figure 1.4:</b> Natural Gait Cycle starting with Heel Strike and ending at Deceleration.....                                  | 5  |
| <b>Figure 1.5:</b> Phases of Normal Gait Cycle.....  | 6  |
| <b>Figure 1.6:</b> (a) Endoskeletal System (b) Exoskeletal System.....   | 7  |
| <b>Figure 1.7:</b> (a) SACH Foot (Passive).....  | 8  |
| <b>Figure 1.7:</b> (b) Powered Ankle Foot (Active) (c) CEME Developed Foot.....  | 9  |
| <b>Figure 2.1:</b> Human ankle biomechanics during natural gait cycle for level ground walking.....                              | 12 |
| <b>Figure 2.2:</b> Human ankle biomechanics during natural gait cycle for stair descent walking.....                             | 13 |
| <b>Figure 2.3:</b> (a) Human ankle biomechanics during natural gait cycle level walking gait.....                                | 14 |
| <b>Figure 2.3:</b> (b) Ankle Angle vs. Ankle Torque for Ankle.....   | 15 |
| <b>Figure 2.4:</b> (a) Motor Neurons from Brain to Muscle activation.....  | 16 |
| <b>Figure 2.4:</b> (b) Schematic of a Neuron.....  | 17 |
| <b>Figure 2.5:</b> EMG Signal Decomposition.....   | 18 |
| <b>Figure 2.6:</b> Structure of a Skeletal Muscle.....   | 19 |
| <b>Figure 2.7:</b> Lower Limb Skeletal Muscles for Movement of Foot and Toe.....   | 20 |
| <b>Figure 2.8:</b> Raw and Filtered EMG Data.....  | 21 |
| <b>Figure 2.9:</b> Control Architecture for Lower Limb Prosthesis.....   | 22 |
| <b>Figure 2.10:</b> Mimicking Results for level ground walking.....  | 22 |
| <b>Figure 2.11:</b> Control system for Eilenberg <i>et al.</i> [19] including a neuromuscular model.....                         | 23 |
| <b>Figure 3.1:</b> Surface activity and Depth of muscle.....   | 25 |
| <b>Figure 3.2:</b> Effect of electrode spacing.....  | 26 |
| <b>Figure 3.3:</b> System model for real time EMG signal recording.....  | 29 |
| <b>Figure 3.4:</b> (a) Filtered EMG signal from Tibialis Anterior Muscle (b) Filtered EMG signal from Gastrocnemius Muscle ..... | 31 |
| <b>Figure 4.1:</b> Flow chart of the Control System.....   | 35 |
| <b>Figure 4.2:</b> Trajectory Generation Block – SIMULINK.....   | 36 |
| <b>Figure 4.3:</b> (a) Conversion Block Ankle to Motor (b) Motor to Ankle Angles .....   | 37 |
| <b>Figure 4.4:</b> PI Controller – SIMULINK.....   | 40 |
| <b>Figure 4.5:</b> Control scheme for Motor Control .....  | 41 |
| <b>Figure 4.6:</b> Output Comparison Block – SIMULINK.....   | 42 |
| <b>Figure 4.7:</b> SIMULINK Model for the Control System.....  | 43 |
| <b>Figure 5.1:</b> Step response of the Output.....  | 44 |
| <b>Figure 5.2:</b> Ankle Angle trajectory for level ground walking.....  | 46 |
| <b>Figure 5.3:</b> Comparison of reference ankle angle trajectory to ankle angles - Initial control system.....                  | 46 |
| <b>Figure 5.4:</b> Flowchart for initial control system.....   | 47 |
| <b>Figure 5.5:</b> Final results achieved from the controller for powered lower limb prosthesis.....                             | 48 |
| <b>Figure 5.6:</b> Results for Ankle Angle and Ankle Torque by S. Au <i>et al.</i> [7].....                                      | 50 |
| <b>Figure 5.7:</b> a) Results for Ankle Torque and (b) Ankle Torque by M. Eilenberg <i>et al.</i> [19].....                      | 51 |

## List of Tables

|   |    |
|---|----|
| <b>Table 3-1:</b> Synthetic EMG and sensors data for level ground walking having 3 states for each muscle input ..... | 28 |
| <b>Table 4-1:</b> Data of the Subject 5 (FJI) for Reference Trajectories.....   | 34 |
| <b>Table 4-2:</b> Motor and Controller Parameters.....  | 38 |
| <b>Table 5-1:</b> Design Requirements for the Closed Loop Control System and Controller Outputs.....                  | 45 |
| <b>Table 5-2:</b> Parameters for Closed Loop Control System for Ankle Angle Control Initially.....                    | 45 |

