DEVELOPMENT OF AN INDIVIDUAL FINGER ABDUCTION AND ADDUCTION MECHANISM FOR A PROSTHETIC HAND

Rajapaksha Arachchillage Gaya Madhusanka Gunawardhana

208834C

Degree of Master of Engineering

Department of Mechanical Engineering

Faculty of Engineering

University of Moratuwa

Sri Lanka

August 2025

DEVELOPMENT OF AN INDIVIDUAL FINGER ABDUCTION AND ADDUCTION MECHANISM FOR A PROSTHETIC HAND

Rajapaksha Arachchillage Gaya Madhusanka Gunawardhana

208834C

Dissertation submitted in partial fulfillment of the requirements for the degree

Master of Engineering in Manufacturing Systems Engineering

Department of Mechanical Engineering

Faculty of Engineering

University of Moratuwa

Sri Lanka

August 2025

DECLARATION

I declare that this is my own work and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date: 12/08/2025

The above candidate has carried out research for the Masters dissertation under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of the Supervisor: Prof. R.A.R.C. Gopura

Signature of the Supervisor: Date: 12/08/2025

Name of the Co-Supervisor: Dr. R.K.P.S. Ranaweera

Signature of the Co-Supervisor: Date: 12/08/2025

DEDICATION

To my dear family, Mom and Dad, your love and support have been my anchor. This thesis is dedicated to you, and I am deeply grateful for your unwavering belief in me.

ACKNOWLEDGMENT

First and foremost, I am extremely grateful to take this opportunity to give my sincere gratitude to my Supervisors Senior Prof. R.A.R.C. Gopura, Dean of Faculty of Graduate Studies, University of Moratuwa, and Dr. Pubudu Ranaweera, Senior Lecture, Department of Mechanical Engineering, University of Moratuwa for their invaluable and motivational advice, continuous supervision, continuous follow-up, and patience throughout the past period to complete my MEng Project.

I want to thank Dr. J.R. Gamage for his technical assistance and ongoing advice in coordinating the PG Dip/M-Eng. Manufacturing Systems Engineering Program.

I would like to thank Mr. Gayan Kanchan Jayasekara, Vice President of Fine Finish Engineering, and Mr. Mafaz Mahroof, Business Development Manager of Fine Finish Engineering, for sponsoring the CNC Machining. I am grateful to all of Fine Finish Engineering's technical staff members who support Machining.

My special thanks go to Mr. Bandara Samarakoon, Assistant Engineer of HITEC Sensors Developments (Pvt.) Ltd, who provided full support for Electronic Design, PCB Fabrications, and Programming. Mr. Harshana Subasinghe and Nilanga Gamage provided full support for 3D printing.

It has been an amazing experience working in an aerospace product design environment. Thanks to everyone at HITEC Sensors Developments (Pvt.) Ltd. Furthermore, I would like to give special thanks to my immediate supervisor, the Technical Service Center Manager, Mr. Hasitha Prasanna, for his invaluable assistance in providing a pleasant working and learning environment.

Finally, I would like to convey my gratitude to my wife and parents. It would have been difficult for me to complete my studies without their unwavering support and encouragement throughout the process.

Lastly, I would like to express my gratitude to everyone who has supported us in the research project directly and indirectly during its development.

ABSTRACT

Hand amputations can occur as a result of accidents, illness, or even war, and that can be physically and psychologically challenging for the amputee. To help individuals with their daily activities and increase their independence, prosthetic hands are used to replace missing hands. Silicone-based cosmetic covers can be used to replicate the aesthetic view of the human hands. In the human hand, there are different finger motions like abduction and adduction, flexion and extension, and opposition and retroposition. Over the years, several mechanisms have been developed for finger flexion and extension. However, finger abduction and adduction are also required to achieve grasping patterns such as power and precision grasping patterns. In this research, the finger abduction and adduction mechanism was developed, and the mechanism is powered by a cam, gear, clutch, and tendon systems. The proposed cam system was designed using six abduction and adduction finger patterns. The middle finger is rigidly attached to the palm, while the little, ring, and index fingers perform individual abduction and adduction motions. A five-bar mechanism is used for the little, ring, middle, and index fingers, and a four-bar mechanism is used for the thumb for the flexion and extension motions. A kinematic study and mobility analysis were conducted on the five-bar mechanism. Furthermore, motion simulation proved that the finger mechanism is capable of flexion and extension motions. Static stress simulations were performed on stress-critical components of the proposed mechanism using a CAD package to ensure mechanical reliability. The prosthetic hand was assembled using 3D-printed and CNC-machined components and actuated by eight micro metal gear motors to get the 18 DOF. Experimental validation proved the capability of individual finger abduction and adduction with grasping patterns like Tripod, Quadpod, and Adduction Grip.

Key Words: Prosthetic Hands, Finger Mechanism, Finger Abduction and Adduction

TABLE OF CONTENTS

DECLARATION i
DEDICATION ii
ACKNOWLEDGMENT iii
ABSTRACT iv
LIST OF FIGURES viii
LIST OF TABLES xii
LIST OF ABBREVIATIONS xiii
LIST OF APPENDICES xv
CHAPTER 1 1
1. INTRODUCTION 1
1.1 Motivation 1
1.2 Aim and Objectives 1
1.2.1 Aim 1
1.2.2 Objectives 1
1.3 Methodology 2
1.4 Overview 2
CHAPTER 2 3
2. LITERATURE REVIEW 3
2.1 Biomechanics of the Human Hand 3
2.1.1 Anatomy of the Human Hand 3
2.1.2 Tendon System of the Human Finger 4
2.1.3 Hand Movement Patterns 5
2.1.4 Types of Grasping Patterns 7
2.1.5 Types of Upper Limb Amputations 10
2.2 Different Types of Prosthetic Hands 10
2.2.1 Single Actuated Prosthetic Hands 11
2.2.2 Multi-Actuated Prosthetic Hands 12
2.2.3 3D Printed Prosthetic Hands 14
2.2.4 Anthropomorphic Prosthetic Hands 17
2.2.5 Prosthetic Hands with Finger Abduction and Adduction 19
2.3 Finger Mechanisms and Actuation Methods of Prosthetic Hands 22
2.3.1 Tendon Systems for Prosthetic Fingers 22
2.3.2 Linkage Mechanisms for Prosthetic Fingers 26

2.3.3 Mechanism for Thumb 32
2.3.4 Belt Drive Systems for Prosthetic Hands 33
2.3.5 SMA for Prosthetic Hands 34
2.3.6 Pneumatic Artificial Muscles for Prosthetic Hands 35
2.3.7 Motors used for Prosthetic Hand Controlling 37
2.4 Prosthetic Hand Controlling Methods 38
2.4.1 EMG Signal-Based Control Methods 38
2.4.2 EEG Signal-Based Control Methods 40
2.4.3 Other Controlling Methods 41
2.5 Aesthetic View of the Prosthetic Hands 42
2.6 Identified Research Gap 43
CHAPTER 3 44
3. MECHANICAL DESIGN OF PROSTHETIC HAND 44
3.1 Selected Mechanisms 44
3.1.1 Finger Flexion and Extension Mechanism 45
3.1.2 Finger Abduction and Adduction Patterns 46
3.1.3 Abduction and Adduction Mechanism 48
3.2 Kinematic Analysis 53
3.2.1 Kinematic Analysis of Five-Bar Linkage 54
3.2.2 Mobility Analysis for the Five-Bar Mechanism 56
3.2.3 Kinematic Representation of the Hand 57
3.3 Design Analysis 60
3.3.1 CAD Design of Prosthetic Hand 60
3.3.2 FEA Simulation of the Abd/Add Mechanism 62
3.4 Motion Analysis 67
3.4.1 Motion Simulation of the Finger 67
3.4.2 CAD Representation of the Mechanism Work 69
3.4.3 Grasps of the Prosthetic Hand 72
3.5 Prototype Fabrication 73
3.5.1 Assembly Part Fabrication 73
3.5.2 Prosthetic Hand Assembly Process 75
CHAPTER 4 78
4. CONTROL SYSTEM OF PROSTHETIC HAND 78
4.1 The Motor Configuration of the Hand 78
4.2 Control Hardware Architecture 79

4.2.1 Pololu Micro Gear Motors 80
4.2.2 Pololu DRV8835 Motor Driver Specification 80
4.2.3 Microcontrollers 81
4.3 Control Algorithm 83
4.4 PCB Design and Fabrication 85
CHAPTER 5 87
5. EXPERIMENTS AND RESULTS 87
5.1 Developed Prosthetic Hand 87
5.2 Experimental Setup and Protocol 88
5.3 Individual Finger Flexion and Extension Patterns 91
5.4 Individual Finger Abduction and Adduction Patterns 96
5.5 Capable Grasping Patterns 98
CHAPTER 6 102
6. DISCUSSION 102
CHAPTER 7 104
7. CONCLUSION 104
REFERENCES 105

LIST OF FIGURES

Figure Description Pages

Figure 2.1 Bones and Joints of the Human Hand[1] 3
Figure 2.2 a. Bones of the Hand, b. Major Joints of the Hand, c. Kinematic Model of the DOFs of the Hand [5] 4
Figure 2.3 Tendon System of a Finger [6] 4
Figure 2.4 Hand Movement Patterns 5
Figure 2.5 Finger Movement Patterns of the Human Hand [9] 6
Figure 2.6 Basic Hand Grasping Patterns 7
Figure 2.7 Hand and Finger Movement Patterns [14] 8
Figure 2.8 Types of Upper Limb Amputations 10
Figure 2.9 Appearance and CAD design of the Rehand 11
Figure 2.10 Single-Actuated Prosthetic Hand 12
Figure 2.11 Yale Myo Adapt Hand 12
Figure 2.12 Prosthetic Hand with 3 Actuators 13
Figure 2.13 The MERO Hand 13
Figure 2.14 KIT Prosthetic and its Components Integrated palm 14
Figure 2.15 SSSA-MyHand 14
Figure 2.16 PUCP University Prosthetic Hand 15
Figure 2.17 CAD Design of EMG-Controlled Prosthetic Hand 15
Figure 2.18 Grasping Patterns of the Tack Hand 15
Figure 2.19 Mechanical Design of the Galileo Hand 16
Figure 2.20 Six DOF Open-Source Hand 16
Figure 2.21 X-Limb Prosthetic Hand 17
Figure 2.22 Smart Bionic Hand 17
Figure 2.23 Anthropomorphic Prosthetic Hand 18
Figure 2.24 Special Thumb Design 18
Figure 2.25 I-Grasp Prosthetic Hand 18
Figure 2.26 3D model of the finger 19
Figure 2.27 Pisa/IIT SoftHand 2 19
Figure 2.28 Finger Abd/Add Prosthetic Hand Gear System 20
Figure 2.29 Dexterous Prosthetic Hand 20
Figure 2.30 TN Hand 21
Figure 2.31 The Tendons paths of the UB Robot Hand 22
Figure 2.32 KIT Prosthetic hand tendon-based system [24] 23
Figure 2.33 The tendon route of the finger 23
Figure 2.34 Principle of Operation of the Tendon-Driven Finger [47] 23
Figure 2.35 Tendon-Driven Prosthetic Hand of SMA Prosthetic Hand 24
Figure 2.36 X Hand Finger Mechanism [13] 24
Figure 2.37 The Interlock Mechanism Used for Tendon-Driven Prosthetic Fingers 24
Figure 2.38 Prosthetic Finger with leaf spring and tendons 25
Figure 2.39 Side view of the Five-Finger Robotic Hand 25
Figure 2.40 Mechanical Design of the Under-Tendon Driven Finger 26
Figure 2.41 Design of the prototype finger [7] 26

Figure 2.42 Mechanism of the Index Finger [9] 27
Figure 2.43 Two four-bar mechanism-based fingers [11] 27
Figure 2.44 Four-bar mechanism finger actuation sequence 28
Figure 2.45 (a) Linkage arrangement of modified CBM (b) Spring mechanism with prismatic joint in modified linkage. 28
Figure 2.46 Cross Bar Mechanism in Finger Abd/Add Prosthetic Hand 29
Figure 2.47 The couple-adaptive mechanism of the finger. 29
Figure 2.48 Finger Joint Coupling Mechanism 30
Figure 2.49 Planetary gear system at the MP joint 30
Figure 2.50 Single-actuator prosthetic hand 31
Figure 2.51 Thumb Flexion and Extension Motion using a gear system 32
Figure 2.52 Thumb Design of the Olympic Prosthetic Hand 32
Figure 2.53 Schematic Finger Actuation 33
Figure 2.54 Schematic Diagram of SCHU Mechanism 33
Figure 2.55 Shape Memory Alloy Prosthetic Hand 34
Figure 2.56 SMA configuration with tendon-driven prosthetic fingers 34
Figure 2.57 Bionic Hand 35
Figure 2.58 Components of the F3 Hand II 35
Figure 2.59 Structure of the Pneumatic Artificial Muscles 36
Figure 2.60 Natural and Curved State of the Pneumatic Artificial Muscles 36
Figure 2.61 Pneumatic Artificial Muscles 36
Figure 2.62 Soft Bionics Prosthetic Hand 37
Figure 2.63 Structure of the Pneumatic Actuators 37
Figure 2.64 Motor Unit 38
Figure 2.65 EMG Signal Extraction 39
Figure 2.66 Bipolar configurations of EMG Signal Extraction 39
Figure 2.67 Eight Muscle Positions on the Right Arm [82] 39
Figure 2.68 Myo Arm Band for EMG Signal Extraction 40
Figure 2.69 Recorded Raw EMG Signal [84] 40
Figure 2.70 EEG Signal Extraction Device 40
Figure 2.71 The arrangement of the Distance Sensor 41
Figure 2.72 Prosthetic Finger and Covered Prosthetic Finger 42
Figure 2.73 Cosmetic cover of the SMA Hand 42
Figure 3.1 3D CAD Model of the Prosthetic Hand 44
Figure 3.2 Actuation Mechanism Selection 45
Figure 3.3 3D Design of the Finger 46
Figure 3.4 3D Design of the Thumb 46
Figure 3.5 Individual Finger Abd/Add Patterns - Little, Ring, and Index Fingers 47
Figure 3.6 Individual Finger Abd/Add Patterns 48
Figure 3.7 Proposed CAM System 49
Figure 3.8 Proposed Cam Shaft for Little, Ring, and Middle Finger Abd/Add Motions 49
Figure 3.9 Gear System of the Hand 50
Figure 3.10 Gear System Mounting 50
Figure 3.11 Detail Design of the Clutch System 51
Figure 3.12 Spring System of the Abd/Add Mechanism 52
Figure 3.13 Spring Calculations for the Compression Springs 52

Figure 3.14 Tendon Pully - Torque Calculation 53
Figure 3.15 Link Configuration for Kinematic Analysis 54
Figure 3.16 Kinematic Structure of the Human Hand 57
Figure 3.17 The Kinematic Structure of the Proposed Prosthetic Hand 58
Figure 3.18 3D Representation of the Kinematic Analysis of the Prosthetic Hand ... 58
Figure 3.19 Compact Palm Design of the Hand 60
Figure 3.20 Dimensions of the Proposed Prosthetic Hand 61
Figure 3.21 1st Load Path of the Abd/Add Mechanism 62
Figure 3.22 Loading Direction of the 1st Load Path 63
Figure 3.23 Boundary Condition of the 1st Load Path 63
Figure 3.24 Mesh Refinement of the 1st Load Path 63
Figure 3.25 Stress Simulation Result of the 1st Load Path 64
Figure 3.26 Second Load Path of the Abd/Add Mechanism 65
Figure 3.27 Boundary Condition of the Second Load Path 65
Figure 3.28 Mesh Refinement of the 2nd Load Path 65
Figure 3.29 Stress Simulation Results of the 2nd Load Path 66
Figure 3.30 Trajectory of Fingertip, DIP, and PIP 67
Figure 3.31 Trajectory of Fingertip, DIP, and PIP in X-Y Plane 67
Figure 3.32 Trajectory of Fingertip, IP of the Thumb 68
Figure 3.33 Trajectory of Fingertip and IP in X-Y Plan 68
Figure 3.34 Fingers Initial Position - CAD Representation of the Clutch and CAM System Work 69
Figure 3.35 Four Fingers Abducted Position - CAD Representation of the Clutch and CAM System Work 69
Figure 3.36 Little Finger Abducted Position - CAD Representation of the Clutch and CAM System Work 70
Figure 3.37 Little and Ring Fingers Abducted Position - CAD Representation of the Clutch and CAM System Work 70
Figure 3.38 Index Finger Abducted Position - CAD Representation of the Clutch and CAM System Work 71
Figure 3.39 Little and Index Fingers Abducted Position - CAD Representation of the Clutch and CAM System Work 71
Figure 3.40 Squeeze - Application of the Individual Abd/Add Motion 72
Figure 3.41 Application of the Abd/Add Motion. (a) Tripod, (b) Quadpod, (c) Sphere 3 Finger, (d) Sphere 4 Finger 72
Figure 3.42 3D Printing Process of Arm and Finger Parts 73
Figure 3.43 Finish Parts of the Arm and Wrist 74
Figure 3.44 Finish Parts of the Finger and Assemble the Finger 74
Figure 3.45 Machined Parts using CNC Lathe, Milling, and EDM Wire Cut Machines 75
Figure 3.46 Worm and Wheel Gears 76
Figure 3.47 Fabricated Five Fingers 77
Figure 3.48 Assembly of the Prosthetic Hand 77
Figure 4.1 The motor configuration of the prosthetic hand 78
Figure 4.2 Hardware Architecture of the Prosthetic Hand 79
Figure 4.3 IN/IN Controlling Mode of the Motor Controller 81
Figure 4.4 Teensy 4.1 Development Board 81

Figure 4.5 Arduino Mega 2560 Development Board..... 82
Figure 4.6 Closed-Loop Control System of the Single Motor Unit..... 83
Figure 4.7 Open-Loop Control Algorithm of the Total System..... 84
Figure 4.8 Fabricated PCB for Teensy 4.1 and Four Motor Controller..... 85
Figure 4.9 Developed Key Pay Array for Motor Selection 85
Figure 4.10 Teensy 4.1 and Arduino Mega Communication Setup..... 86
Figure 4.11 Fabricated Hardware Setup..... 86
Figure 5.1 The Developed Prosthetic Hand 87
Figure 5.2 Experimental Setup..... 89
Figure 5.3 Initial Finger Position of the Hand 91
Figure 5.4 Individual Finger F/E. (a) - Little Finger Flexion, (b) - Ring Finger Flexion, (c) - Middle Finger Flexion, (d) - Index Finger Flexion..... 91
Figure 5.5 Start of End Position of the Index Finger Flexion and Extension Motion 92
Figure 5.6 Start of End Position Angles of the Index Finger Flexion and Extension Motion..... 92
Figure 5.7 Proposed Index Finger Joints Trajectory..... 92
Figure 5.8 Index Finger Trajectory of the Human Hand 93
Figure 5.9 Graph of Angle Variation with Time..... 93
Figure 5.10 Finger F/E. (a) - Little & Ring Fingers Flexion, (b) - Little, Ring & Middle Fingers Flexion, (c) - Ring and Middle Fingers Flexion, (d) - All Four Fingers Flexion 94
Figure 5.11 Flexion and Extension of the Thumb..... 94
Figure 5.12 Start of End Position of the Thumb Flexion and Extension Movements 95
Figure 5.13 Start of End Position Angles of the Thumb Flexion and Extension Motion 95
Figure 5.14 Actual Thumb Joints Trajectory 95
Figure 5.15 Graph of Angle Variation with Time 96
Figure 5.16 Four Finger Adduction and Abduction Position..... 96
Figure 5.17 Finger Abduction and Adduction. (a) - Little Finger Adduction, (b) - Little and Ring Finger Adduction, (c) - Index Finger Adduction, (d) Little and Index Finger Adduction..... 97
Figure 5.18 Abduction angle of the Index Finger..... 97
Figure 5.19 Thumb Abduction and Adduction 98
Figure 5.20 Grasping Pattern for the Individual Abduction and Adduction. (a) - Tripod, (b) - Quadpod, (c) - Power Sphere..... 98
Figure 5.21 Squeeze of a Syringe 99
Figure 5.22 Steps of the Squeeze of a Syringe..... 99
Figure 5.23 Common Grasping Patterns. (a) - Pinch Grip - Small Ball, (b) - Pinch Grip - Small Disk, (c) - Lateral Grip 99
Figure 5.24 Power Grip - Holding a Small Cylinder and a Large Cylinder 100
Figure 5.25 Power Grip - Holding a Small and a Large Disk..... 100
Figure 5.26 Grasping Patterns (a) Index Pointing (b) Pinch Grip..... 101

LIST OF TABLES

Table **Description** **Pages**

Table 2.1 Finger Motion Range 6
Table 2.2 Summary of Abduction and Adduction Grasping Patterns 9
Table 2.3 Abduction and Adduction Prosthetic Hand Comparison 21
Table 2.4 Joint Motion of the SMA Hand 34
Table 3.1 Mesh Details of 1st Load Path FEA Simulation 63
Table 3.2 Material Properties of SS304 64
Table 3.3 Mesh Details of the 2nd Load Path Simulation 66
Table 3.4 Material Properties of 15/5 PH 66
Table 3.5 Bearing Sizes and Number of Bearings 75
Table 3.6 Types of Springs and Number of Springs 76
Table 3.7 Worm and Wheel System Specifications 76
Table 4.1 Motor Locations and Motor Functions 79
Table 4.2 Gear Motors Specification 80
Table 4.3 Specifications of the Motor Drive 80
Table 4.4 Features of Teensy 4.1 82
Table 4.5 Features of the Arduino Mega Development Board 83
Table 5.1 Specifications of the Prosthetic Hand 88
Table 5.2 Experimental Protocol F/E Motions 89
Table 5.3 Experimental Protocol Abd/Add Motions 90
Table 5.4 Experimental Protocol: Grasping Patterns 90
Table 5.5 Range of Motion Comparison 101

LIST OF ABBREVIATIONS

Abbreviation	Description
3D	Three Dimensional
Abd	Abduction
Abd/Add	Abduction and Adduction
ABS	Acrylonitrile Butadiene Styrene
ADL	Activities of Daily Living
Add	Adduction
ATM	Automated Teller Machine
AU	Actuation Unit
BCI	Brain Computer Interface
BDC	Brushed Direct Current
BLDC	Brushless Direct Current
BMI	Brain Machine Interface
CAD	Computer-Aided Design
CMB	Cross Bar Mechanism
CMC	Carpometacarpal
CNC	Computer Numerical Control
CO_2	Carbon Dioxide
CORE	Compliant Rolling-Contact Element
DC	Direct Current
DIP	Distal Interphalangeal
Dip	Diploma
DOA	Degree of Actuation
DOF	Degrees of Freedom
DPGS	Double Planetary Gear System
Dr.	Doctor
ECoG	Electrocorticogram
EDM	Electrical Discharge Machining
EEG	Electroencephalogram
EMG	Electromyography
EOG	Electrooculogram
F/E	Flexion/ Extension
FEA	Finite Element Analysis
FMG	Fiber Force Myography
IP	Interphalangeal
ISO	International Organization for Standardization
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MEng	Master of Engineering
MCP	Metacarpophalangeal

Abbreviation	Description
MMG	Mechanomyography
NiTi	Nickel Titanium
PAM	Pneumatic Artificial Muscles
PCB	Printed Circuit Board
PDM	Pulse Width Modulation
PG	Postgraduate
PGS	Planetary Gear System
PIP	Proximal Interphalangeal
PLA	Polylactic Acid
Prof	Professor
Pvt Ltd	Private Limited Company
RAM	Random Access Memory
RC	Radio-Carpal
RGB	Red, Green, and Blue
RFID	Radio Frequency Identification
ROM	Read Only Memory
SMA	Shape Memory Alloy
SMG	Ultrasound Imaging
SS	Stainless Steel
TPU	Thermoplastic Polyurethane
USB	Universal Serial Bus

LIST OF APPENDICES

Table	Description	Pages
Appendix A :	Sample Mechanical Drawing	114
Appendix B :	Components of the Finger Assembly	115
Appendix C :	Components of the Abd/Add Mechanism	117
Appendix D :	Arduino Code of Teensy 4.1 & Arduino Mega	119
Appendix E :	PCB Schematic Diagram	132