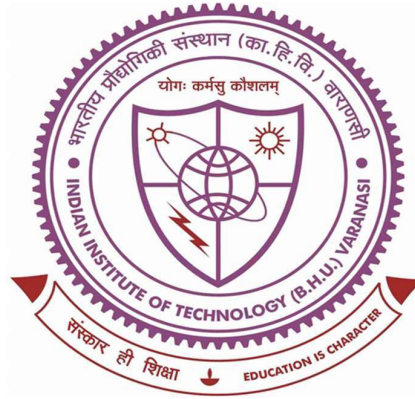


***WEARABLE SENSORS BASED GAIT ACQUISITION
FOR MOTION ANALYSIS AND PROSTHETIC
ANKLE-FOOT DESIGN***



**Thesis submitted in partial fulfilment
for the Award of Degree
*Doctor of Philosophy***

**by
*SACHIN NEGI***

***SCHOOL OF BIOMEDICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI – 221005***

18021008

January 2022

CERTIFICATE

It is certified that the work contained in the thesis titled "**WEARABLE SENSORS BASED GAIT ACQUISITION FOR MOTION ANALYSIS AND PROSTHETIC ANKLE-FOOT DESIGN**" by "**Sachin Negi**" has been carried out under my supervision and it has not been submitted elsewhere for a degree.

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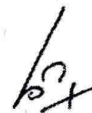
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Indian Institute of Technology
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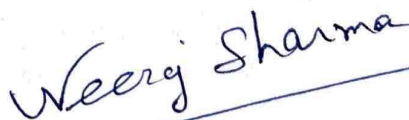


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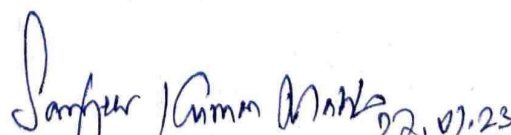
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- SACHIN NEGI

CONTENTS

<i>Certificate</i>	<i>iii</i>
<i>Declaration by the Candidate</i>	<i>iv</i>
<i>Copyright Transfer Certificate</i>	<i>v</i>
<i>Acknowledgements</i>	<i>vi</i>
<i>Contents</i>	<i>ix</i>
<i>List of Figures</i>	<i>xiii</i>
<i>List of Tables</i>	<i>xvii</i>
<i>LIST of Abbreviations</i>	<i>xix</i>
<i>Preface</i>	<i>xxiv</i>
1 INTRODUCTION.....	1
1.1 Challenges in Gait Analysis.....	3
1.2 Challenges in Ankle-Foot Prostheses	4
1.3 Objectives of the Thesis.....	4
1.4 Contribution of the Thesis.....	5
1.5 Organization of the Thesis.....	6
2 THEORETICAL BACKGROUND.....	7
2.1 Gait Analysis and Gait Phase Detection Techniques.....	7
2.2 Usefulness of Gait Analysis.....	17
2.3 Lower Limb Prosthetic Devices.....	18
2.4 Machine Learning Techniques.....	33
2.5 Performance Metrics for Machine Learning Classification.....	37
2.6 Conclusion.....	38

**3 HUMAN LOCOMOTION CLASSIFICATION FOR DIFFERENT TERRAINS
USING MACHINE LEARNING TECHNIQUES.....39**

3.1 Introduction40

3.2 Implementation of Machine Learning Techniques for Gait Analysis43

3.3 Materials and Methods44

 3.3.1 Data Collection.....44

 3.3.2 Data Analysis.....46

 3.3.3 Machine Learning-Based Predictive Model.....46

 3.3.4 Feature Selection.....47

3.4 Results and Discussion.....49

3.5 Conclusion.....59

**4 FSR AND IMU SENSORS-BASED HUMAN GAIT PHASE DETECTION AND
ITS CORRELATION WITH EMG SIGNAL FOR DIFFERENT TERRAIN
WALK..... 61**

4.1 Introduction63

4.2 Materials and Methods.....67

 4.2.1 Sensor Module.....67

 4.2.2 Signal Conditioning.....68

 4.2.3 Heuristic Rules and Zero-Crossing Algorithm-based Gait Phase Detection....70

 4.2.3.1 Gait phase detection using FSR sensors.....70

 4.2.3.2 Gait phase detection using IMU sensors.....72

 4.2.4 Gait Sub-phase Detection using Fuzzy Logic Implementation in Arduino.....74

 4.2.4.1 Fuzzy logic for gait phase detection.....74

 4.2.4.2 Adaptive Neuro-Fuzzy Inference Systems.....75

4.2.5 Wireless Sensor Network.....	76
4.3 Results and Discussion.....	77
4.3.1 Gait Phase Detection using FSR Sensors.....	78
4.3.2 Gait Phase Detection using IMU Sensors.....	80
4.3.3 Synchronization of FSR, IMU, and EMG Sensors Data.....	82
4.3.4 Gait Phase Detection using Fuzzy Logic Implemented in Arduino IDE.....	85
4.4 Conclusion.....	88
5 CLASSIFICATION OF HUMAN FOOT MOVEMENTS FOR ANKLE-FOOT PROSTHESIS CONTROL USING MACHINE LEARNING AND FUZZY LOGIC TECHNIQUES	89
5.1 Introduction.....	91
5.2 Material and Methods.....	94
5.2.1 Human Lower-Limb Motion.....	94
5.2.2 Data Acquisition.....	96
5.2.3 Machine Learning Approaches for Movement Classification.....	104
5.2.4 Ankle-Foot Prosthesis Control in Sagittal Plane.....	106
5.3 Results and Discussion.....	107
5.3.1 Raspberry Pi based Classification.....	107
5.3.2 Arduino Nano 33 BLE based Classification.....	112
5.3.2.1 TinyML based prediction.....	112
5.3.2.2 Fuzzy logic-based prediction.....	114
5.4 Conclusion.....	118
6 DESIGN AND ANALYSIS OF MAGNETORHEOLOGICAL DAMPER-BASED ANKLE-FOOT PROSTHESIS PROTOTYPE.....	119

6.1 Introduction	120
6.2 Material and Methods.....	121
6.2.1 Ankle-Foot Prosthesis Models.....	122
6.2.2 Magnetorheological Damper: Application in Lower-Limb Prosthesis.....	124
6.2.3 MR Damper Specifications.....	125
6.2.4 MR Damper Controller.....	126
6.2.5 Prototype Working.....	130
6.3 Results and Discussion.....	132
6.3.1 Prosthetic Foot Analysis.....	132
6.3.2 Leaf Spring Analysis.....	134
6.3.3 A Summary of Amputation and Prosthesis Design	135
6.4 Conclusion.....	136
7 CONCLUSIONS AND FUTURE SCOPE	137
7.1 Conclusions	137
7.2 Future Work	139
APPENDIX A GUI for Gait Analysis	141
APPENDIX B Printed Circuit Boards	142
APPENDIX C Ethical Clearance Certificate	144
APPENDIX D Consent Statement of Amputee	145
BIBLIOGRAPHY	147
LIST OF PUBLICATIONS	159

LIST OF FIGURES

Figure 1-1: Disabled population by type of disability in India (Census, 2011)	1
Figure 1-2: Disabled population by type of disability in Uttarakhand (Census, 2011)	2
Figure 2-1: The types of lower limb amputations.....	19
Figure 2-2: Below-knee vs. Above-knee Prosthesis.....	19
Figure 2-3: Two orthosis control methods: proportional EMG control and footswitch control.....	27
Figure 2-4: Block diagram of the prosthesis system.....	29
Figure 2-5: The three designs of SPARKy 1, 2, and 3.....	29
Figure 2-6: The prototype and CAD model of PANTOE 1.....	31
Figure 3-1: EMG and X- Acceleration signals acquired from right leg TA and MGAS muscles for five different terrain walks.....	46
Figure 3-2: Workflow diagram of machine learning-based predictive modelling.....	47
Figure 3-3: EMG-envelope for different terrains and corresponding Gait events detected using acceleration signal.....	51
Figure 3-4: Scatter plot for EMG data from two muscles for (a) RMS, (b) IAV, (c) WL, and (d) MAV1 features	52
Figure 3-5: Error Rate vs. K- values.....	56
Figure 3-6: Confusion matrix of DNN classifier for Subject-03 (a) 10-trials training dataset, (b) unseen data.....	59
Figure 4-1: Gait cycle (Stride).....	63
Figure 4-2: Wireless system for gait analysis.....	68
Figure 4-3: Signal conditioning for FlexiForce piezoresistive force sensor	69

Figure 4-4: (a)Weight versus Resistance and (b)Weight versus Voltage curves for FlexiForce sensors.....	70
Figure 4-5: Flow chart of the gait phase detection algorithm using the FSR sensor.....	71
Figure 4-6: Flow chart of the gait phase detection algorithm using the IMU sensor	73
Figure 4-7: Arduino Nano-based data acquisition system.....	74
Figure 4-8: Model Structure of ANFIS [using MATLAB]	75
Figure 4-9: Gait phase detection using 2-FSR sensors (a) Right leg, (b) Left leg.....	78
Figure 4-10: Real-time gait phase detection using 4-FSR sensors.....	79
Figure 4-11: Gyroscope readings of IMU sensor attached at the shank for different gait patterns: (a) LG, (b) RD, (c) RA, (d) SD, (e) SA	82
Figure 4-12: Real-time gait phase detection using a single IMU sensor	82
Figure 4-13: Synchronization of FSR, IMU, and EMG sensors data for different gait patterns: (a) LG, (b) RD, (c) RA, (d) SD, (e) SA.....	84
Figure 4-14: Training data error (GPD using FSR and IMU sensor data).....	86
Figure 4-15: Average Testing data error(GPD using FSR and IMU sensor data).....	86
Figure 4-16: Rule Viewer window for the trained model (FSR and IMU sensor data).....	87
Figure 5-1: Foot movements: dorsiflexion and plantarflexion, eversion and inversion, lateral and medial rotation.....	95
Figure 5-2: Average EMG patterns for a subject for different foot positions: (a) FF, (b) DF, (c) PF, (d) IN, (e) EV, (f) MR, and (g) LR.....	100
Figure 5-3: Average FMG patterns for a subject for different foot positions: (a) FF, (b) DF, (c) PF, (d) IN, (e) EV, (f) MR, and (g) LR.....	104
Figure 5-4: ML-based foot movement prediction for ankle-foot prosthesis control.....	105
Figure 5-5: Encoder DC servo motor control using: (a) EMG sensors, (b) FSR sensors ...	106

Figure 5-6: Ankle-foot prosthesis control in sagittal plane: (a) dorsiflexion, (b) foot-flat, and (c) plantarflexion	107
Figure 5-7: Classification accuracy for 3, 5, and 7-foot positions using different classifiers for EMG.....	109
Figure 5-8: Classification accuracy for 3, 5, and 7-foot positions using different classifiers for FMG	111
Figure 5-9: TinyML model performance for the classification of 3, 5, and 7-foot positions using EMG	112
Figure 5-10: TinyML model performance for the classification of 3, 5, and 7-foot positions using FMG.....	113
Figure 5-11: Training data error (Foot movement classification for EMG signal).....	114
Figure 5-12: Average Testing data error (Foot movement classification for EMG signal)	115
Figure 5-13: Training data error (Foot movement classification for FMG signal).....	116
Figure 5-14: Average Testing data error (Foot movement classification for FMG signal)	116
Figure 6-1: Workflow diagram for Arduino based ankle-foot prosthesis control.....	122
Figure 6-2: Force-velocity curve for MR damper.....	126
Figure 6-3: Circuit for Arduino Nano-based MR damper control.....	127
Figure 6-4: Voltage and current output of MR damper circuit for 3 different positions of potentiometer: (a) 0%, (b) 29%, and (c) 100%.....	130
Figure 6-5: CAD models for prosthetic foot prototypes	131
Figure 6-6: Transtibial amputee walking on MR damper-based ankle-foot prosthesis prototype.....	132
Figure 6-7: Analysis of Prosthetic foot prototype during heel strike.....	133

Figure 6-8: Analysis of Prosthetic foot prototype during mid-stance	133
Figure 6-9: Analysis of Prosthetic foot prototype during toe-off.....	134
Figure 6-10: Analysis of leaf spring.....	135
Figure A-1: Graphical user interface (GUI) for gait analysis using FSR, IMU, and EMG sensors	141
Figure A-2: GUI options for the selection of serial port, baud rate and number of samples to record	141
Figure A-3: GUI options to record new raw sensor data, and display the recorded waveform	141
Figure B-1: Printed circuit board 2-D view for gait analysis using FSR, IMU, and EMG sensors	142
Figure B-2: Schematic diagram of the circuit for gait analysis using FSR, IMU, and EMG sensors	142
Figure B-3: Printed circuit board 2-D view for Arduino Nano-based MR damper control	143
Figure B-4: Schematic diagram for Arduino Nano-based MR damper control circuit	143

LIST OF TABLES

Table 2-1: Summary of Gait Analysis Survey using Camera and Image Processing.....	9
Table 2-2: Summary of Gait Analysis Survey using Wearable Sensors/IMUs/Foot-insole Sensors	11
Table 2-3: Summary of Survey on Prosthetic Leg Controls.....	21
Table 2-4: Machine Learning Classifiers.....	35
Table 3-1: Classification accuracy of LDA classifier.....	53
Table 3-2: Classification accuracy of KNN classifier.....	53
Table 3-3: Classification accuracy of DT classifier.....	54
Table 3-4: Classification accuracy of RF classifier.....	54
Table 3-5: Classification accuracy of SVM (RBF-kernel) classifier.....	54
Table 3-6: Classification accuracy of SVM (Poly-kernel) classifier.....	55
Table 3-7: Classification accuracy of DNN classifier [with feature extraction].....	55
Table 3-8: Classification accuracy of DNN classifier [without feature extraction].....	55
Table 3-9: Comparison of classification accuracy and evaluation time of classifiers for the testing of single trial data of each class.....	57
Table 4-1: Gait parameters using two- FSR sensors.....	79
Table 4-2: Gait parameters using IMU sensors.....	80
Table 4-3: Prediction Accuracy for Gait sub-phases.....	87
Table 5-1: ML Classifier performance for three sagittal plane foot positions [for EMG]..	108
Table 5-2: Confusion matrix and performance evaluation metrics for SVC classifier to classify foot positions using subject-2 EMG signals: (a) 3-class, (b) 5-class, and (c) 7- class.....	110
Table 5-3: ML Classifier performance for three sagittal plane foot positions [for FMG]..	111

Table 5-4: Confusion matrix and performance evaluation metrics for TinyML classifier to classify the foot movements in the sagittal plane for a transtibial amputee.....	113
Table 5-5: Fuzzy logic performance for EMG signal to classify three- foot movements...	115
Table 5-6: Fuzzy logic performance for FMG signal to classify three- foot movements...	117
Table 6-1: MR damper specifications.....	126
Table 6-2: MR damping control using a Potentiometer	128
Table 6-3: Analysis results for different foot positions	134
Table 6-4: A summary of amputation and prosthesis design.....	136

LIST Of ABBREVIATIONS

AB	Able-Bodied
ABS	Acrylonitrile Butadiene Styrene
AAFO	Active Ankle-Foot Orthosis
AFO	Ankle-Foot Orthosis
AI	Artificial Intelligence
AMAL	Adaptive Modular Active Leg
AMP	Ankle Mimicking Prosthetic
ANFIS	Adaptive Neuro-Fuzzy Inference System
BF	Biceps Femoris
BK	Below-Knee
BLDC	Brushless Direct Current
CATIA	Computer Aided Three-Dimensional Interactive Application
CW	Clockwise
CCW	Counter-Clockwise
CD	Controlled Dorsiflexion
CF	Conventional Feet
CP	Controlled Plantarflexion
CWT	Continuous Wavelet Transform
DD	Direct Drive
DNN	Deep Neural Network
DT	Decision Tree
EBA	Entropy-Based Adaptation
EEG	Electroencephalography
EK	Expert Knowledge

EKS	Explicit Knowledge Store
EMG	Electromyography
ER	Energy Requirements
ES	Erector Spinae
ESR	Energy-Storing-and-Returning
FDM	Fused Deposition Modeling
FE	Finite Element
FES	Functional Electrical Stimulation
FGCD	Foot-Ground Contact Detection
FIS	Fuzzy Inference System
FMG	Force-myography
FS	Floor Sensors
FSR	Force-Sensitive Resistor
GA	Genetic Algorithm
GB	Gradient Boosting
GNB	Gaussian Naive Bayes
GPD	Gait Phase Detection
GPDS	Gait-Phase Detection Sensor
GRF	Ground Reaction Force
GUI	Graphical User Interface
HS	Heel-Strike
I2C	Inter-Integrated Circuit
IAV	Integrated Absolute Value
IC	Initial Contact
IMU	Inertial Measurement Unit

IP	Image Processing
ISW	Initial Swing
KNN	K- Nearest Neighbor
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LG	Level Ground
LGAS	Lateral Gastrocnemius
Li-Po	Lithium-Polymer
LLA	Lower-Limb Amputation
LR	Loading Response
MACCEPA	Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator
MAV	Mean Absolute Value
MGAS	Medial Gastrocnemius
ML	Machine Learning
MLPNN	Multilayer Perceptron Neural Networks
MR	Magnetorheological
MST	Mid Stance
MSW	Mid-Swing
MT-1	Metatarsal-1
MT-5	Metatarsal-5
NN	Neural Network
P/O	Prosthetic and Orthotic
PANTOE	Powered Ankle and Toe
PCA	Principal Component Analysis
PCB	Printed Circuit Board

PF	Plantarflexion
PL	Peroneus Longus
PLA	Polylactic Acid
PO	Push-Off
PP	Powered Plantarflexion
PSO	Particle Swarm Optimization
PSW	Pre-Swing
RA	Ramp Ascent
RBF	Radial Basis Function
RD	Ramp Descent
ReLU	Rectified Linear Units
RF	Rectus Femoris
RMS	Root Mean Square
SA	Stair Ascent
SACH	Solid Ankle Cushion Heel
SAFE	Stationary Attachment Flexible Endoskeletal
SD	Stair Descent
SEA	Series Elastic Actuator
sEMG	Surface Electromyography
SENIAM	sEMG for the Non-invasive Assessment of Muscle
SO	Soleus
SoM	Self-Organizing Map
SPARKy	Spring Ankle with Regenerative KINETICS
SS	Stainless-Steel
SSI	Simple Square Integral

SVC	Support Vector Classification
SVM	Support Vector Machine
SW	Swing
TA	Tibialis Anterior
ToF	Time-of-Flight
TO	Toe-Off
TFA	Transfemoral Amputee
TM	Temporal Moments
TST	Terminal Stance
TSW	Terminal Swing
TTA	Transtibial amputee
ULDA	Uncorrelated Linear Discriminant Analysis
VA	Vastus Lateralis
VAR	Variance
VSA	Variable-Stiffness Actuator
WL	Waveform Length
WSN	Wireless Sensor Network

PREFACE

The thesis work presents the step-by-step procedure needed to be adopted to develop and evaluate robust below-knee prosthesis based on an adaptive intent recognition system that continually incorporates neural information through (i) electromyography (EMG) and (ii) kinetic and kinematic information acquired through mechanical sensors. Different aspects of designing lower limb prostheses have been studied to achieve this goal, including the human gait analysis for different terrains. The primary social utilization of this work is to help the amputee those are living in hilly areas. Further, for comparative analysis, a gait study has been performed by experimenting on healthy persons using wearable sensors for five different walking patterns: (i) level ground, (ii) ramp ascent, (iii) ramp descent, (iv) stair ascent, and (v) stair descent. The present study compares and presents prosthetic devices proposed or available to date for lower limb amputees, mainly ankle-foot prostheses.

After the broad overview and literature survey, the thesis can be divided into two major parts. First, the thesis work focuses on the gait analysis and gait phase detection techniques used in real-time to generate the control signal for the prosthetic leg. Different types of sensors are used and compared to provide real-time detection using different algorithms such as thresholding, heuristics rules, fuzzy logic, and machine learning (ML) approaches. In the second part, the thesis work presents different control strategies for the actuators and dampers used to design and develop a powered ankle-foot prosthesis prototype. The research work focuses on designing power ankle-foot prostheses, which can be afforded by middle-class amputees living in developing countries like India to mimic human-like movement. Of course, the design must be lightweight, battery-operated, and the controller operation in real-time.

Chapter 1 presents the introduction of the thesis, which states the current issues, objectives, and thesis contributions. Chapter 2 discusses the literature background for gait phase detection using different kinds of sensors and algorithms. The chapter explains the applications of gait analysis, the major focus in realizing the prosthetic foot to mimic human locomotion. This chapter also briefs the literature survey about different types of prosthetic foot in the market. Various ML algorithms are also introduced, later tested on healthy and amputee subjects in later chapters.

Chapter 3 introduces different ML algorithms for the classifications of human locomotion in five different terrains: Level Ground, Ramp Ascent, Ramp Descent, Stair Ascent, and Stair Descent. Hybrid sensor (EMG and accelerometer) technology is used in the proposed work to record the signal from two leg muscles: tibialis anterior and medial gastrocnemius for each leg. In chapter 4, Force-sensitive resistor (FSR) and inertial measurement unit (IMU) sensors are used to detect the gait phase in real-time; later, these are correlated with EMG signals for the above five terrains. The heuristic rules, zero-crossing, and fuzzy logic algorithms are employed for gait phase detection. MATLAB's Neuro-Fuzzy toolbox is used for the training purpose using labeled data that later predict the current gait phase.

Chapter 5 presents the different ML techniques to classify the following foot movements: dorsiflexion, plantarflexion, inversion, eversion, medial rotation, and lateral rotation. The purpose is to design a real-time standalone computing system to predict the foot movements in the sagittal plane, useful for ankle-foot prosthesis control. The present study acquires EMG and force-myography (FMG) signals from the leg's tibialis anterior, medial gastrocnemius, lateral gastrocnemius, and peroneus longus muscles. These are tested for their suitability to provide ML/ TinyML based control options to control prosthetic devices. The response of two kinds of processors, i.e., Raspberry Pi and Arduino Nano 33 BLE, is compared for real-time prediction.

Here the Arduino Nano controller has the limitation of memory; for overcoming this limitation, the latest Arduino Nano 33 BLE controller is suggested that can store more rules. Also, it is comparatively faster in performance when we focused on real-time applications. This chapter also includes the performance of fuzzy logic controllers for the ankle-foot movement classification problem of the previous chapter using EMG and FMG signals.

Further, Chapter 6 proposes designing and developing an ankle-foot prosthesis prototype using magnetorheological damper and 3D printer technology. The CAD model of the prosthetic foot, leaf spring, retention spring, and the various connecting parts required to connect the pylon and damper actuator assemblies are designed using CAD software. The fused deposition modeling 3D printer-based technique prints a prosthetic foot and other connecting parts using ABS filament. The prototype consists of two control parts: the first part controls the magnetorheological actuator that absorbs the impacts during walking. The second part is the control of the electric actuator intended to generate the dorsiflexion and plantarflexion movements. Finally, the prototype is tested on a transtibial amputee under the supervision of a prosthetist. In Chapter 7, the overall thesis contribution has been enlisted along with its future directions. It might be beneficial for further research in this field.

Dedicated to

My Parents,

My wife PRERNA NEGI,

&

My children RUTHVIKA, IPSHITA, & ISHAAN

