

**DEVELOPMENT OF AN ADAPTIVE WEIGHT
SHIFTING TRAINING SYSTEM FOR IMPROVED
REHABILITATION OUTCOMES IN INDIVIDUALS
WITH LOWER LIMB AMPUTATION**

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**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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by

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Submitted

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to the



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Dedicated

To

Grandparents

CERTIFICATE

This is to certify that the thesis entitled “**Development of an Adaptive Weight Shifting Training System for Improved Rehabilitation Outcomes in Individuals With Lower Limb Amputation,**” submitted by **Mr. Sirsendu Sekhar Mishra (2019EEZ8375)** for the award of the degree of **Doctor of Philosophy** to Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the bonafide research work carried out by him under our supervision and guidance. He has fulfilled the requirements for submission of this thesis, which, to the best of our knowledge, has reached the requisite standard.

The contents of this thesis have not been submitted in part or in full to any other University or Institute for the award of any other degree or diploma.

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Sirsendu Sekhar Mishra

ABSTRACT

Millions of individuals with lower limb amputations encounter considerable challenges in maintaining postural stability as compared to able-bodied individuals due to the loss of sensory feedback and limited joint movement in passive prostheses. This instability leads to frequent falls and hinders rehabilitation progress. It is understood that a prosthetic device with a suitable torque delivery is necessary to avoid such complications. This dissertation focuses on estimating the corrective torque required from external assistive devices, such as powered exoskeletons and prosthetics, by utilizing postural control techniques to enhance inter-limb coordination.

In the context of powered exoskeletons and prostheses, a prior assessment of corrective action using a computational method facilitates the selection of an appropriate actuator that delivers necessary joint torque while maintaining postural stability. Consequently, an effective computational model of gait initiation that incorporates neuromuscular system parameters becomes essential prior to the design of such prosthetic devices. Estimating the required corrective torque is a recognized challenge in this field. As an initial study, an inverted pendulum (IP) model-based approach of healthy individuals was explored to model the postural dynamics in individuals with lower limb amputation. The main objective of the current study was to estimate the external torque required from an external assistive device using a postural model-based control technique to maintain the postural balance. The IP model and a suitable control strategy were validated through simulation studies using kinematic data recorded from four healthy individuals and four individuals with lower amputation.

To compensate for postural balance asymmetries during inter-limb coordination, individuals with lower extremity amputation over-depend on visual inputs and somatosensory information from the intact limb. This additional demand leads to higher mental engagement and an additional flexion and extension torque in the sound limb, resulting in the asymmetrical weight distribution between the limbs and the unacceptability of current passive prostheses. To address such issues, a biomechanically relevant ankle-foot prosthesis model with a suitable model-based control approach was explored to estimate the required control torque on the prosthetic ankle joint during dynamic balance tasks in different visual conditions. The postural model and the control technique were validated through simulation studies using kinematic data recorded from six individuals with lower amputation. The results indicate that the effectiveness of the proposed approach has a significant potential to accommodate balancing

uncertainties in different visual conditions by addressing the design-oriented challenges in prosthetic solutions.

While estimating desired corrective torque, existing prosthetic-based postural control approaches acknowledge challenges in accounting for diverse biomechanical variations in real-time, further impacting the efficacy of the rehabilitation outcomes. To address this, a novel biomimetic motor-driven ankle-foot prosthesis prototype was initially developed to follow the intact limb trajectory collected from three amputated individuals by delivering corrective action. Later, a data-driven adaptive control-based bench-top model was designed and implemented to achieve real-time closed-loop trajectory tracking performance. Specifically, this approach aimed to record the reference trajectory from the intact limb and deliver the required torque to the prosthetic side by utilizing a data-driven adaptive control method to enhance inter-limb coordination. The benchtop model was tested through simulated scenarios using kinematic data recorded from ten individuals with different levels of unilateral lower amputation. Results illustrate that the proposed approach could reduce the asymmetrical weight bearing on the intact limb and enhance rehabilitation outcomes in prosthetic users.

It is crucial to validate the concept of the closed-loop data-driven adaptive control mechanism in a clinical setting. Furthermore, it is essential to investigate the performance of such a training approach on different levels of amputation (transtibial and transfemoral), different visual conditions (eyes open and eyes closed), and different directions for balancing exercises. To address these aspects, an innovative in-house training platform was designed and fabricated to explore the application of corrective feedback on the postural balance in unilateral lower limb amputees. The training platform employs a data-driven, model-independent control architecture to deliver corrective torque to the prosthetic limb based on measurements taken from the intact limb during balancing tasks. Consequently, the corrective torque facilitates the prosthetic limb to enhance inter-limb coordinated control. Eight participants with lower limb amputations consented to participate in this study. The efficacy of the proposed training platform was assessed using different performance matrices between the intact and prosthetic limbs. The findings indicate that corrective feedback delivered by the proposed training platform is more efficacious in unilateral lower limb amputees during balancing tasks.

सार

निचले अंग विच्छेदन वाले लाखों व्यक्तियों को निष्क्रिय कृत्रिम अंगों में संवेदी प्रतिक्रिया की हानि और सीमित संयुक्त आंदोलन के कारण सक्षम व्यक्तियों की तुलना में आसन स्थिरता बनाए रखने में काफी चुनौतियों का सामना करना पड़ता है। यह अस्थिरता बार-बार गिरने का कारण बनती है और पुनर्वास की प्रगति में बाधा डालती है। ऐसी जटिलताओं से बचने के लिए उपयुक्त टॉर्क डिलीवरी वाला कृत्रिम उपकरण आवश्यक है। इस शोध प्रबंध में, अनुसंधान अध्ययनों ने अंतर-अंग समन्वय को बढ़ाने के लिए आसन नियंत्रण तकनीकों का उपयोग करते हुए, बाहरी सहायक उपकरणों, जैसे कि संचालित एक्सोस्केलेटन और प्रोस्थेटिक्स से आवश्यक सुधारात्मक टॉर्क का अनुमान लगाने पर ध्यान केंद्रित किया है।

संचालित एक्सोस्केलेटन और कृत्रिम उपकरणों के मामले में, एक कम्प्यूटेशनल दृष्टिकोण के माध्यम से सुधारात्मक टॉर्क का पूर्व अनुमान उपयुक्त एक्ज्यूटर का चयन करने में मदद करता है जो आसन संतुलन बनाए रखते हुए एक उपयुक्त संयुक्त टॉर्क प्रदान करता है। नतीजतन, सहायक उपकरणों को डिजाइन करने से पहले न्यूरोमस्क्युलर सिस्टम घटकों के लिए चाल आरंभ का एक कुशल कम्प्यूटेशनल मॉडल आवश्यक है। हालांकि, वांछित सुधारात्मक टॉर्क का अनुमान लगाना इस डोमेन में एक स्वीकृत चुनौती है। प्रारंभिक अध्ययन के रूप में, निचले अंग के विकलांगों में आसन गतिशीलता को मॉडल करने के लिए स्वस्थ व्यक्तियों के एक उल्टे पेंडुलम (आईपी) मॉडल-आधारित दृष्टिकोण की खोज की गई थी। इस अध्ययन का मुख्य उद्देश्य आसन संतुलन बनाए रखने के लिए आसन मॉडल-आधारित नियंत्रण तकनीक का उपयोग करके बाहरी सहायक उपकरण से आवश्यक बाहरी टॉर्क का अनुमान लगाना था।

अंतर-अंग समन्वय के दौरान आसन संतुलन विषमताओं की भरपाई करने के लिए, निचले अंग विच्छेदन वाले व्यक्ति अक्षुण्ण अंग से दृश्य इनपुट और सोमैटोसेंसरी जानकारी पर अत्यधिक निर्भर होते हैं। यह अतिरिक्त मांग उच्च मानसिक जुड़ाव और अक्षुण्ण अंग में अतिरिक्त विस्तार और फ्लेक्सन टॉर्क की ओर ले जाती है, जिससे अंगों के बीच विषम भार वितरण और वर्तमान निष्क्रिय कृत्रिम अंगों की अस्वीकार्यता होती है। ऐसे मुद्दों को संबोधित करने के लिए, विभिन्न दृश्य स्थितियों में गतिशील संतुलन कार्यों के दौरान कृत्रिम टखने के जोड़ पर आवश्यक नियंत्रण टॉर्क का अनुमान लगाने के लिए एक उपयुक्त मॉडल-आधारित नियंत्रण दृष्टिकोण के साथ एक बायोमेकैनिकली प्रासंगिक टखने-पैर कृत्रिम अंग मॉडल की खोज की गई थी। छह निचले अंग विच्छेदन वाले व्यक्तियों से रिकॉर्ड किए गए गतिज डेटा का उपयोग करके सिमुलेशन अध्ययनों के माध्यम से आसन मॉडल और नियंत्रण तकनीक को मान्य

किया गया। परिणाम संकेत देते हैं कि प्रस्तावित दृष्टिकोण की प्रभावशीलता में कृत्रिम समाधानों में डिज़ाइन-उन्मुख चुनौतियों को संबोधित करके विभिन्न दृश्य स्थितियों में संतुलन अनिश्चितताओं के अनुकूल होने की बहुत संभावना है।

वांछित सुधारात्मक टॉर्क का अनुमान लगाते समय, वर्तमान प्रोस्थेटिक-आधारित आसन नियंत्रण दृष्टिकोण वास्तविक समय में विविध बायोमैकेनिकल विविधताओं के लिए जिम्मेदार होने में चुनौतियों को स्वीकार करते हैं, जो पुनर्वास परिणामों की प्रभावकारिता को और अधिक प्रभावित करते हैं। इसे संबोधित करने के लिए, सुधारात्मक कार्रवाई प्रदान करके तीन विच्छेदित व्यक्तियों से एकत्र किए गए अक्षुण्ण अंग प्रक्षेप पथ का अनुसरण करने के लिए एक नया बायोमिमेटिक मोटर-चालित टखने-पैर प्रोस्थेसिस प्रोटोटाइप शुरू में विकसित किया गया था। बाद में, एक डेटा-संचालित अनुकूली नियंत्रण-आधारित बेंच-टॉप मॉडल को वास्तविक समय के बंद-लूप प्रक्षेप पथ ट्रेकिंग प्रदर्शन को प्राप्त करने के लिए डिज़ाइन और कार्यान्वित किया गया था। विशेष रूप से, इस दृष्टिकोण का उद्देश्य अक्षुण्ण अंग से संदर्भ प्रक्षेप पथ को रिकॉर्ड करना और अंतर-अंग समन्वय को बेहतर बनाने के लिए डेटा-संचालित अनुकूली नियंत्रण दृष्टिकोण की अवधारणा का उपयोग करके आवश्यक टॉर्क प्रोस्थेटिक पक्ष को वितरित करना था। बेंच-टॉप मॉडल का परीक्षण एकतरफा निचले विच्छेदन के विभिन्न स्तरों वाले दस व्यक्तियों से रिकॉर्ड किए गए कीनेमेटिक डेटा का उपयोग करके कुछ नकली परिदृश्यों के माध्यम से किया गया था। परिणाम बताते हैं कि प्रस्तावित दृष्टिकोण अक्षुण्ण अंग पर असममित भार वहन को कम कर सकता है और प्रोस्थेटिक उपयोगकर्ताओं में पुनर्वास परिणामों को बढ़ा सकता है।

क्लिनिकल सेटिंग में क्लोज्ड-लूप डेटा-संचालित अनुकूली नियंत्रण तंत्र की अवधारणा को मान्य करना महत्वपूर्ण है। विच्छेदन के विभिन्न स्तरों (ट्रांसटिबियल और ट्रांसफेमोरल), विभिन्न दृश्य स्थितियों (आंखें खुली और बंद), और संतुलन अभ्यासों के लिए विभिन्न दिशाओं पर इस तरह के प्रशिक्षण दृष्टिकोण के प्रदर्शन की जांच करना आवश्यक है। इसे संबोधित करने के लिए, एकतरफा निचले अंग के विच्छेदित व्यक्तियों के आसन संतुलन पर सुधारात्मक प्रतिक्रिया के अनुप्रयोग का पता लगाने के लिए एक अभिनव इन-हाउस प्रशिक्षण प्लेटफ़ॉर्म डिज़ाइन और निर्मित किया गया था। प्रशिक्षण प्लेटफ़ॉर्म डेटा-संचालित मॉडल-स्वतंत्र नियंत्रण वास्तुकला का उपयोग करता है ताकि संतुलन कार्यों के दौरान बरकरार अंग के माप का उपयोग करके कृत्रिम अंग पर सुधारात्मक टॉर्क प्रदान किया जा सके। नतीजतन, सुधारात्मक टॉर्क अंतर-अंग समन्वित नियंत्रण को बढ़ाने के लिए कृत्रिम अंग की सुविधा प्रदान करता है। निचले अंग विच्छेदन वाले आठ प्रतिभागियों ने इस अध्ययन में भाग लेने के लिए सहमति व्यक्त की। प्रस्तावित प्रशिक्षण प्लेटफ़ॉर्म की प्रभावकारिता का मूल्यांकन बरकरार और कृत्रिम अंगों के बीच विभिन्न प्रदर्शन

मैट्रिक्स का उपयोग करके किया गया था। निष्कर्ष यह दर्शाते हैं कि प्रस्तावित प्रशिक्षण मंच द्वारा दिया गया सुधारात्मक फीडबैक संतुलन कार्यों के दौरान एकतरफा निचले अंग विकलांगों में अधिक प्रभावकारी है।

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LIST OF ABBREVIATIONS

CoM	Centre of Mass
LLA	Lower Limb Amputees
IP	Inverted Pendulum
AFP	Ankle-Foot Prosthesis
WSTS	Weight-Shifting Training System
WSE	Weight Shifting Exercises
LTI	Linear Time Invariant
CDM	Coefficient Diagram Method
SISO	Single Input Single Output
CDM-PID	Coefficient Diagram Method-based Proportional Integral Derivative
RMSE	Root Mean Square of Error
<i>h</i> PSO-CDM-PID	Hybrid Particle Swarm Optimization- Coefficient Diagram Method based Proportional Integral Derivative
<i>f</i> -IMC-PID	Fractional filter- Internal Model Control-based Proportional Integral Derivative
CFDL	Compact Form of Dynamic Linearization
PPD	Pseudo Partial Derivative
NTD	Neural Transmission Delay
GRF	Ground Reaction Force
CoP	Centre of Pressure
EEG	Electroencephalogram
WSTP	Weight Shifting Training Platform
SUS	System Usability Scale
SLC	Spinal Like Controller
LFC	Load Frequency Control
LQG	Linear Quadratic Gaussian
EC	Evolutionary Computation
CNC	Computer Numerical Control
AMP	Amputee Mobility Predictor
MBC	Model-Based Control
ABS	Acrylonitrile Butadiene Styrene

EO	Eyes Open
EC	Eyes Closed
PD	Parkinson's Disease
MAE	Mean Absolute Error
MSE	Mean Square Error
LIP	Linear Inverted Pendulum
WHO	World Health Organization
SA	Single Axis
CNS	Centra Nervous System
EMG	Electromyography
SACH	Solid Ankle Cushion Heel