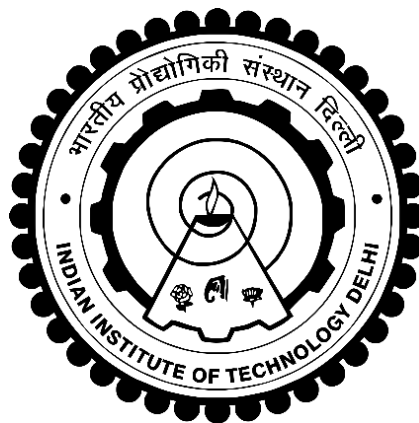


BIOMECHANICAL MODELING AND INTERVENTION DEVELOPMENT FOR DIABETIC FOOT ULCERS

GURPREET SINGH



CENTRE FOR BIOMEDICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2025

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**Biomechanical Modeling and Intervention
Development for Diabetic Foot Ulcers**

by

Gurpreet Singh

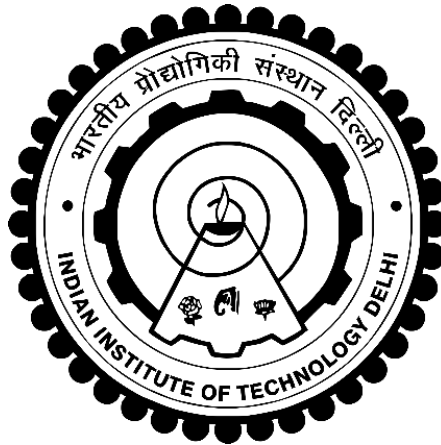
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Submitted

in fulfilment of the requirements for the award of the degree of

Doctor of Philosophy

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*This Ph.D. thesis is dedicated to my parents for their endless
love, sacrifices, and belief in my dreams.*

*To my supervisor for his invaluable mentorship and
belief in my potential, and*

*To my friends, who stood by me through the highs and lows
of this Ph.D. journey.*

Certificate

This is to certify that the thesis entitled *“Biomechanical Modeling and Intervention Development for Diabetic Foot Ulcers”*, submitted by **Mr. Gurpreet Singh (2020BMZ8123)**, a full-time Ph.D. scholar and Prime Minister’s Research Fellow, at the Centre for Biomedical Engineering, Indian Institute of Technology Delhi, is a record of original research work carried out by him under my supervision and guidance.

This dissertation fulfils all the requirements as per the Institute regulations, and in my opinion, it has attained the standard necessary for the award of the degree of Doctor of Philosophy (Ph.D.). To the best of my knowledge, neither this thesis nor any part of it has been submitted elsewhere for the award of any other degree or diploma at any University or Institute.



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Gurpreet Singh

Abstract

Diabetic foot ulceration is the most frequent outcome of diabetes and is more probable to be of neuropathic origin. To date, a plethora of studies have focused on diabetic foot and ulcer prevention. However, limited studies have investigated the biomechanics of diabetic foot ulceration. The focus of this thesis is the extensive biomechanical modeling of diabetic foot ulcers. Also, a novel modular diabetic insole was designed and fabricated to effectively offload the abnormal or peak plantar pressures in diabetic patients. The pressure values at the plantar region were quantified using an in-house developed plantar pressure measuring insole. The effectiveness of the modular diabetic insole was tested quantitatively and qualitatively to assess its performance. Chapter 1 presents a detailed background of diabetes, diabetic foot, and ulceration development, emphasizing the pathophysiology and principles of management of the diabetic foot. This chapter discusses the motivation, significance, problem statement, and research gap in the biomechanical modeling and management of diabetic foot ulcers.

Chapter 2 provides an overview of diabetic foot complications and ulceration. This chapter covers the biomechanics of foot structure, plantar pressure distribution, and a detailed review of the existing computational models for diabetic foot ulcers. Also, various medical interventions and clinical practices used for the treatment of diabetic foot ulcers were discussed to find the research gaps and technological advancements needed in this area. Chapter 3 focuses on the biomechanical modeling of diabetic ulcers in different foot types. Computational models of both normal foot and flatfoot were developed and simulated with varying ulcer diameters and depths to quantify plantar stresses and assess ulcer risks across these foot types. Building on this work, Chapter 4 explores the biomechanical modeling of diabetic ulcers across all possible locations on the foot. The results were analyzed in terms of pressure distribution and ulcer risk at each location, with a discussion on the implications of ulcer location for clinical interventions.

Chapter 5 details the development of a smart pressure measurement insole designed to measure the plantar pressure values. It provides an in-depth discussion of the pressure measurement insole's design, sensor integration, functionality, and validation. A data collection study was conducted to evaluate its effectiveness in measuring pressure offloading values. Chapter 6 focuses on the design concept and rationale behind the development of the modular insole. Its effectiveness was validated through a comparative study involving two groups: 15 healthy participants and 15 diabetic participants. This study demonstrated the efficacy of the modular insole using experimental results. Finally, Chapter 7 summarizes the key findings of the thesis, highlighting their implications for diabetic foot management, clinical practice, patient care, and scientific research. Additionally, it outlines potential directions for future investigations and clinical applications. The findings of the work present important information on the foot condition post-ulceration and may help identify possibilities of further ulceration in the diabetic foot. In addition, the findings of this thesis are anticipated to be indispensable for developing suitable interventions (e.g., custom orthotics) for diabetic foot ulcer management.

अमूर्त

मधुमेही पैर का अल्सर मधुमेह का सबसे आम परिणाम है और इसके तंत्रिकाविकृति संबंधी होने की संभावना अधिक होती है। अब तक, मधुमेही पैर और अल्सर की रोकथाम पर कई अध्ययन केंद्रित रहे हैं। हालाँकि, सीमित अध्ययनों ने मधुमेही पैर के अल्सर के बायोमैकेनिकल मॉडलिंग की जाँच की है। इस शोध प्रबंध का केंद्र बिंदु मधुमेही पैर के अल्सर के व्यापक बायोमैकेनिकल मॉडलिंग पर है। इसके अलावा, मधुमेही रोगियों में असामान्य या चरम तलीय दबाव को प्रभावी ढंग से कम करने के लिए एक नवीन मॉड्यूलर मधुमेही इनसोल डिज़ाइन और निर्मित किया गया था। एक स्व-विकसित तलीय दबाव मापक इनसोल का उपयोग करके तलीय क्षेत्र में दबाव के मानों को परिमाणित किया गया। मॉड्यूलर मधुमेही इनसोल की प्रभावशीलता का मात्रात्मक और गुणात्मक परीक्षण किया गया ताकि इसके प्रदर्शन का आकलन किया जा सके। अध्याय 1 मधुमेही पैर, मधुमेही पैर और अल्सर के विकास की विस्तृत पृष्ठभूमि प्रस्तुत करता है, जिसमें मधुमेही पैर के प्रबंधन के पैथोफिज़ियोलॉजी और सिद्धांतों पर ज़ोर दिया गया है। यह अध्याय मधुमेही पैर के अल्सर के बायोमैकेनिकल मॉडलिंग और प्रबंधन में प्रेरणा, महत्व, समस्या विवरण और शोध अंतराल पर चर्चा करता है।

अध्याय 2 मधुमेही पैर की जटिलताओं और अल्सरेशन का अवलोकन प्रदान करता है। यह अध्याय पैर की संरचना के बायोमैकेनिक्स, तलीय दाब वितरण, और मधुमेही पैर के अल्सर के मौजूदा कम्प्यूटेशनल मॉडलों की विस्तृत समीक्षा को शामिल करता है। साथ ही, इस क्षेत्र में आवश्यक शोध अंतरालों और तकनीकी प्रगति का पता लगाने के लिए मधुमेही पैर के अल्सर के उपचार में प्रयुक्त विभिन्न चिकित्सा हस्तक्षेपों और नैदानिक पद्धतियों पर चर्चा की गई। अध्याय 3 विभिन्न प्रकार के पैरों में मधुमेही अल्सर के बायोमैकेनिकल मॉडलिंग पर केंद्रित है। सामान्य पैर और चपटे पैर, दोनों के कम्प्यूटेशनल मॉडल विकसित किए गए और विभिन्न अल्सर व्यास और गहराई के साथ उनका अनुकरण किया गया ताकि तलीय तनावों को मापा जा सके और इन प्रकार के पैरों में अल्सर के जोखिमों का आकलन किया जा सके। इस कार्य के आधार पर, अध्याय 4 पैर के सभी संभावित स्थानों पर मधुमेही अल्सर के बायोमैकेनिकल मॉडलिंग का अन्वेषण करता है। परिणामों का विश्लेषण प्रत्येक स्थान पर दाब वितरण और अल्सर के जोखिम के संदर्भ में किया गया, साथ ही नैदानिक हस्तक्षेपों के लिए अल्सर के स्थान के निहितार्थों पर भी चर्चा की गई।

अध्याय 5 में तलीय दाब मानों को मापने के लिए डिज़ाइन किए गए एक स्मार्ट दाब मापक इनसोल के विकास का विवरण दिया गया है। यह दाब मापक इनसोल के डिज़ाइन, सेंसर एकीकरण, कार्यक्षमता

और सत्यापन पर गहन चर्चा प्रदान करता है। दाब भार-मुक्ति मानों को मापने में इसकी प्रभावशीलता का मूल्यांकन करने के लिए एक डेटा संग्रह अध्ययन किया गया था। अध्याय 6 मॉड्यूलर इनसोल के विकास के पीछे की डिज़ाइन अवधारणा और तर्क पर केंद्रित है। इसकी प्रभावशीलता को दो समूहों: 15 स्वस्थ प्रतिभागियों और 15 मधुमेह प्रतिभागियों: के तुलनात्मक अध्ययन के माध्यम से सत्यापित किया गया था। इस अध्ययन ने प्रायोगिक परिणामों का उपयोग करके मॉड्यूलर इनसोल की प्रभावकारिता को प्रदर्शित किया। अंत में, अध्याय 7 थीसिस के प्रमुख निष्कर्षों का सारांश प्रस्तुत करता है, और मधुमेही पैर प्रबंधन, नैदानिक अभ्यास, रोगी देखभाल और वैज्ञानिक अनुसंधान के लिए उनके निहितार्थों पर प्रकाश डालता है। इसके अतिरिक्त, यह भविष्य के अनुसंधान और नैदानिक अनुप्रयोगों के लिए संभावित दिशाओं की रूपरेखा प्रस्तुत करता है। इस कार्य के निष्कर्ष अल्सरेशन के बाद पैर की स्थिति के बारे में महत्वपूर्ण जानकारी प्रस्तुत करते हैं और मधुमेही पैर में आगे अल्सरेशन की संभावनाओं की पहचान करने में मदद कर सकते हैं। इसके अतिरिक्त, इस थीसिस के निष्कर्षों को मधुमेह पैर अल्सर प्रबंधन के लिए उपयुक्त हस्तक्षेप (जैसे, कस्टम ऑर्थोटिक्स) विकसित करने के लिए अपरिहार्य माना जाता है।

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List of Abbreviations

DM	Diabetes Mellitus
IDF	International Diabetes Federation
DFU	Diabetic Foot Ulcers
CAGR	Compound Annual Growth Rate
FEM	Finite Element Modeling
FEA	Finite Element Analysis
TCC	Total Contact Cast
CT	Computed Tomography
MRI	Magnetic Resonance Imaging
TPU	Thermoplastic Polyurethane
IDE	Integrated Development Environment
AZP	Average Zonal Pressure