

# **MODELLING OF SLIP AND FALL RISK OF WORN FOOTWEAR**

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**CENTRE FOR BIOMEDICAL ENGINEERING  
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# **MODELLING OF SLIP AND FALL RISK OF WORN FOOTWEAR**

by

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## Certificate

This is to certify that the dissertation entitled **Modelling of Slip and Fall Risk of Worn Footwear**, submitted by **Mr. Shubham Gupta**, a PhD student and Prime Minister's Research Fellow, in the *Centre for Biomedical Engineering, Indian Institute of Technology, Delhi, India*, for the award of the degree of **Doctor of Philosophy (Ph.D.)**, is a record of an original research work carried out by him under my supervision and guidance. The dissertation fulfils all requirements as per the regulations of this Institute and in my opinion has reached the standard needed for submission. Neither this dissertation nor any part of this has been submitted for any degree or academic award elsewhere.



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## Abstract

One of the main causes of occupational injuries worldwide is slips and falls. These are some of the main sources of risks at work, in leisure activities, in the industrial sector, and when doing routine tasks. A number of lower limb issues, including muscle inflammation, ligament rips, and dislocations, are frequent outcomes of slip and fall accidents. Employees in the US have taken emergency medical vacations as a result of these problems, which has caused a major work delay and an overall financial cost of more than \$170 billion. An sudden decrease in grip at the shoe-floor contact is said to be the main cause of inadvertent slips being initiated. Thus, it becomes crucial to research footwear's traction performance as well as other pertinent features in order to maintain sufficient shoe-floor friction.

Wear reduces a shoe's ability to maintain friction because of its tread properties, which significantly affects the available coefficient of friction (ACOF) at the shoe-floor contact. It was discovered that wearing worn shoes might raise the chance of slipping by up to ten times compared to wearing brand-new (or unworn) shoes. Furthermore, the ACOF at the shoe-floor interface is known to be influenced by a number of footwear-related characteristics, including tread design, flooring type, outsole materials, shoe hardness, and the presence of slippery contaminants. Specifically, the ACOF is significantly reduced when viscous pollutants are present on a floor, increasing the chance of sliding. Additionally, understanding an outsole's performance in both dry and wet sliding conditions depends heavily on its geometrical characteristics, or treads. Due to worn footwear, there is no information available to determine the replacement thresholds, which would allow the user to make an informed decision about whether or not to replace the footwear. Therefore, figuring out the replacement thresholds for these shoes and comprehending the growing risk of slipping will be made easier by knowing how wear affects the traction performance of shoes.

There is a lack of current techniques and technologies in order to measure the slipping risks due to footwear. Most friction measuring devices are bulky, costly, and installed in labs. This is due to their inability to replicate the biomechanics of human slides and the environmental fidelity required to replicate walking floors and contamination conditions that are typical of slip and fall accidents. They also lack portability. Additionally, there is little to no knowledge of slip testing in low- or middle-income nations, and these equipment are costly and hard to come by. Existing slip testing devices have their limitations, so it would be ideal to have a portable, lightweight, and inexpensive device that can simulate human slip biomechanics and

measure traction performance on realistic slippery floors. In addition to this, there is a lack of computational framework for rapid testing of footwear designs in worn conditions. Thus the major focus of this dissertation was to design and develop a biofidelic, portable robotic slip testing device and extensively assess the traction performance of worn footwear through experiments and numerical modelling.

This thesis investigates slips and falls by analyzing their mechanisms, biomechanics, and quantification. Chapter 1 introduces the topic, highlighting its prevalence through statistical data and emphasizing the importance of studying footwear biomechanics and wear to understand slipping. The chapter also explores mechanical slip testing devices for injury quantification.

Chapter 2 provides a literature review on slip testing devices and footwear traction, showcasing various mechanical devices used to measure slipping risks. It stresses the need for biofidelic testing to accurately assess footwear safety. Additionally, computational modeling of footwear-floor interactions is discussed, revealing a lack of rapid computational models for assessing slipping risks considering material wear. Chapter 3 describes the development of a portable, biofidelic whole-shoe robotic slip testing device. The device was validated across multiple footwear-floor-contaminant conditions and proved useful in clinical and non-clinical settings. Chapter 4 uses this device to examine the effect of progressive wear on formal footwear traction in workplace environments, correlating worn areas with frictional performance.

In Chapter 5, the developed device was used to assess the friction in footwear worn by nurses in high-movement hospital areas, using enclosure circles as an ergonomic tool to evaluate slipping risks and propose replacement thresholds. Chapter 6 investigates how tread patterns affect friction, showing that thinner treads and wider gaps increase wet friction, while oblique patterns provide the highest friction in both dry and wet conditions. Finally, Chapter 7 introduces a CFD-based computational model to evaluate tread wear in wet conditions. Validated by experimental testing, the model effectively predicts slipping risks over different wear durations.

## अमूर्त

दुनिया भर में व्यावसायिक चोटों के मुख्य कारणों में से एक फिसलन और गिरना है। ये काम पर, अवकाश गतिविधियों में, औद्योगिक क्षेत्र में और नियमित कार्य करते समय जोखिम के कुछ मुख्य स्रोत हैं। मांसपेशियों में सूजन, लिगामेंट रिप्स और डिस्लोकेशन सहित कई निचले अंग संबंधी समस्याएं, फिसलन और गिरने की दुर्घटनाओं के अक्सर परिणाम होते हैं। इन समस्याओं के परिणामस्वरूप अमेरिका में कर्मचारियों ने आपातकालीन चिकित्सा अवकाश लिया है, जिसके कारण काम में बड़ी देरी हुई है और कुल मिलाकर 170 बिलियन डॉलर से अधिक की वित्तीय लागत आई है। जूते-फर्श संपर्क पर पकड़ में अचानक कमी अनजाने में फिसलन शुरू होने का मुख्य कारण माना जाता है। इसलिए, जूते-फर्श घर्षण को पर्याप्त बनाए रखने के लिए जूते के कर्षण प्रदर्शन के साथ-साथ अन्य प्रासंगिक विशेषताओं पर शोध करना महत्वपूर्ण हो जाता है।

घिसाव के कारण जूते के चलने के गुणों के कारण घर्षण बनाए रखने की जूते की क्षमता कम हो जाती है, जो जूते-फर्श संपर्क पर उपलब्ध घर्षण गुणांक (ACOF) को महत्वपूर्ण रूप से प्रभावित करता है। यह पाया गया कि घिसे हुए जूते पहनने से एकदम नए (या बिना पहने) जूते पहनने की तुलना में फिसलने की संभावना दस गुना तक बढ़ सकती है। इसके अलावा, जूते-फर्श इंटरफेस पर ACOF को कई फुटवियर से संबंधित विशेषताओं से प्रभावित माना जाता है, जिसमें ट्रेड डिज़ाइन, फ्लोरिंग का प्रकार, आउटसोल सामग्री, किनारे की कठोरता और फिसलन वाले दूषित पदार्थों की उपस्थिति शामिल है। विशेष रूप से, जब फर्श पर चिपचिपे प्रदूषक मौजूद होते हैं, तो ACOF काफी कम हो जाता है, जिससे फिसलने की संभावना बढ़ जाती है। इसके अतिरिक्त, सूखी और गीली दोनों तरह की फिसलन स्थितियों में आउटसोल के प्रदर्शन को समझना इसकी ज्यामितीय विशेषताओं या ट्रेड पर बहुत अधिक निर्भर करता है। घिसे हुए जूतों के कारण, प्रतिस्थापन सीमा निर्धारित करने के लिए कोई जानकारी उपलब्ध नहीं है, जो उपयोगकर्ता को जूते बदलने या न बदलने के बारे में सूचित निर्णय लेने की अनुमति देगा। इसलिए, इन जूतों के लिए प्रतिस्थापन सीमा का पता लगाना और फिसलने के बढ़ते जोखिम को समझना यह जानकर आसान हो जाएगा कि पहनने से जूतों के कर्षण प्रदर्शन पर क्या प्रभाव पड़ता है। जूते के कारण फिसलने के जोखिम को मापने के लिए वर्तमान तकनीकों और प्रौद्योगिकियों की कमी है।

अधिकांश घर्षण मापने वाले उपकरण भारी, महंगे होते हैं और प्रयोगशालाओं में लगाए जाते हैं। ऐसा इसलिए है क्योंकि वे मानव स्लाइड के बायोमैकेनिक्स और चलने वाले फर्श और संदूषण की स्थितियों को दोहराने के लिए आवश्यक पर्यावरणीय निष्ठा की नकल करने में असमर्थ हैं जो फिसलने और गिरने की

दुर्घटनाओं के लिए विशिष्ट हैं। उनमें पोर्टेबिलिटी की भी कमी है। इसके अतिरिक्त, निम्न या मध्यम आय वाले देशों में फिसलन परीक्षण के बारे में बहुत कम या कोई जानकारी नहीं है, और ये उपकरण महंगे हैं और मिलना मुश्किल है। मौजूदा फिसलन परीक्षण उपकरणों की अपनी सीमाएँ हैं, इसलिए एक पोर्टेबल, हल्का और सस्ता उपकरण होना आदर्श होगा जो मानव फिसलन बायोमैकेनिक्स का अनुकरण कर सके और यथार्थवादी फिसलन वाले फर्श पर कर्षण प्रदर्शन को माप सके। इसके अलावा, घिसी हुई स्थितियों में फुटवियर डिज़ाइनों के तेज़ परीक्षण के लिए कम्प्यूटेशनल ढाँचे की कमी है। इस प्रकार इस शोध प्रबंध का मुख्य ध्यान एक बायोफिडेलिक, पोर्टेबल रोबोटिक फिसलन परीक्षण उपकरण को डिज़ाइन और विकसित करना और प्रयोगों और संख्यात्मक मॉडलिंग के माध्यम से घिसे हुए जूतों के कर्षण प्रदर्शन का व्यापक रूप से आकलन करना था। यह थीसिस फिसलन और गिरने की क्रियाविधि, बायोमैकेनिक्स और परिमाणीकरण का विश्लेषण करके जांच करती है।

अध्याय 1 विषय का परिचय देता है, सांख्यिकीय आंकड़ों के माध्यम से इसकी व्यापकता पर प्रकाश डालता है और फिसलन को समझने के लिए फुटवियर बायोमैकेनिक्स और घिसाव का अध्ययन करने के महत्व पर बल देता है। अध्याय चोट के परिमाणीकरण के लिए यांत्रिक फिसलन परीक्षण उपकरणों की भी पड़ताल करता है। अध्याय 2 फिसलन परीक्षण उपकरणों और फुटवियर कर्षण पर एक साहित्य समीक्षा प्रदान करता है, जो फिसलन जोखिमों को मापने के लिए उपयोग किए जाने वाले विभिन्न यांत्रिक उपकरणों को प्रदर्शित करता है। यह फुटवियर सुरक्षा का सटीक आकलन करने के लिए बायोफिडेलिक परीक्षण की आवश्यकता पर बल देता है। इसके अतिरिक्त, फुटवियर-फर्श इंटरैक्शन के कम्प्यूटेशनल मॉडलिंग पर चर्चा की गई है, जो सामग्री के घिसाव पर विचार करते हुए फिसलन जोखिमों का आकलन करने के लिए तीव्र कम्प्यूटेशनल मॉडल की कमी को उजागर करता है। अध्याय 4 इस उपकरण का उपयोग कार्यस्थल के वातावरण में औपचारिक फुटवियर कर्षण पर प्रगतिशील पहनने के प्रभाव की जांच करने के लिए करता है, पहने हुए क्षेत्रों को घर्षण प्रदर्शन के साथ सहसंबंधित करता है। अध्याय 5 में, विकसित डिवाइस का उपयोग उच्च-आंदोलन वाले अस्पताल क्षेत्रों में नर्सों द्वारा पहने जाने वाले फुटवियर में घर्षण का आकलन करने के लिए किया गया था, फिसलने के जोखिमों का मूल्यांकन करने और प्रतिस्थापन थ्रेसहोल्ड का प्रस्ताव करने के लिए एक एर्गोनोमिक उपकरण के रूप में संलग्नक हलकों का उपयोग किया गया था। अध्याय 6 जांच करता है कि ट्रेड पैटर्न घर्षण को कैसे प्रभावित करते हैं, यह दिखाते हुए कि पतले ट्रेड और व्यापक अंतराल गीले घर्षण को बढ़ाते हैं, जबकि तिरछे पैटर्न सूखी और गीली दोनों स्थितियों में उच्चतम घर्षण प्रदान करते हैं। अंत में, अध्याय 7 गीली स्थितियों में ट्रेड पहनने का मूल्यांकन करने के लिए CFD-आधारित कम्प्यूटेशनल मॉडल पेश करता है।

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# List of Abbreviations

<b>Abbreviation</b>	<b>Meaning</b>
ACOF	Available Coefficient of Friction
ANOVA	Analysis of Variance
AIIMS	All Indian Institute of Medical Science
ASTM	American Society for Testing and Materials
BLS	Bureau of Labor Statistics
BMI	Body Mass Index
BPT	British Pendulum Tester
BPST	British Portable Skid tester
COP	Centre of Pressure
COF	Coefficient of Friction
CAD	Computer Aided Design
DCOF	Dynamic Coefficient of Friction
EA	Elderly Aged
FF	Formal Footwear
Fv1 and Fv2	Normal Forces
Fx, Fy, and Fz	Ground Response Forces
GRF	Ground Reaction Force
HPS	Horizontal Pull Slipmeter
HOV	Homogeneous Vinyl
HTV	Heterogeneous Vinyl
HP	Horizontal Patterns
ICU	Intensive Care Unit
NSC	National Safety Council
NSR	Non-Slip Resistant
OPD	Outpatient Department
PAST	Portable Articulated Strut Tribometer
PFT	Portable Friction Tester
PSS	Peak sliding speed

p	Profiled
PU	Polyurethane
PLA	Polylactic Acid
RCOF	Required Coefficient of Friction
Ra	Average Surface Roughness
r	Rough
S	Smooth
Sr	Slightly Rough
SR	Slip Resistant
SS	Slip Start
SLS	Sodium Laurel Sulphate
STF	Slip, Trip and Falls
SCOF	Static Coefficient of Friction
SEM	Scanning Electron Microscopy
TNO	Toegepast Natuurwetenschappelijk Onderzoek
TPU	Thermoplastic Polyurethane
UK	United Kingdom
vr	Very Rough
V0	Initial Velocity
VGRF	Vertical Ground Reaction Force
VP	Vertical Patterns
WLI	White Light Interferometry

# List of Symbols

<b>Symbols</b>	<b>Meaning</b>
$R^2$	Coefficient of Determination
Pa	Pascals
$\rho u_i$	Change of momentum per unit mass
$\mu$	Viscosity
$\bar{u}$	Mean velocity