Preface

Background and Motivation

Fall incidents from slips or trips have been recognized as a major threat to the safety of individuals not only in industry but also in daily living. They represent the second leading cause of accidental death, after motor vehicle accidents. Measurements of slipperiness, specifically slip resistance performance, have shown a significant role in identifying slip and fall incidents, in understanding slip and fall mechanisms, and in the development and evaluation of slip and fall prevention strategies.

One of the most generally and commonly practiced methods for the fall safety assessment is to measure a shoe-floor grip or slip resistance property as a form of coefficient of friction. Although the concept of friction is relatively simple and straightforward, solving the real-world problems on slip and fall incidents are a quite complex and challenging task. Therefore, this book aims to offer readers to uncover valuable information for a better understanding on the multifaceted nature of slip resistance properties amongst the shoes, floors and environments, learn objective ways to measuring slip resistance properties and consequently improve pedestrian fall safety assessments.

This book is intended to be an applied engineering guidebook in which the presented concepts and information on slip resistance measurements are provided with a number of graphical forms. The associated quantifying equations and formulae have kept as simple as possible. They controlled to those encountered in lecture and laboratory courses taken in the undergraduate engineering education.

This book is also written for two reader groups: (1) technical and (2) non-technical audiences. Chapter summaries at the end of each chapter are simplified reviews of the chapters' contents and important issues, which are intended for the non-technical reader.

This book brings some of the most important current research related to slips and falls and slip resistance measurements. The book can partly be a textbook and partly a monograph. It is a textbook because it gives a detailed introduction to slip resistance measurement techniques and applications. It is simultaneously a monograph because it presents several new concepts, theories, results, and further developments on slip resistance measurements and fall safety assessments. As a result of its twofold characters, this book is likely to be of interest to undergraduate and postgraduate students. This book can also be used as a handbook to engineers, industry safety consultant and practitioners, and scientists in the field of safety and industrial engineering. One can read this book through sequentially, but it is not necessary since each chapter is essentially self-contained, with as few cross-references as possible.

Main Aims of This Book

This book aims to improve the validity and reliability of slip resistance measurements from an engineering point of view where principal understandings on the shoe-floor friction and wear behaviours can be made. Therefore, this book proposes readers to find valuable information for better understanding of the complex nature of slip resistance properties amongst the shoes, floors and environments, discover objective ways to measuring slip resistance properties and learn to improve pedestrian fall safety assessments.

Readers may not only acquire solid theoretical foundations for accounting the underlying complex mechanisms of slip resistance properties but also enhance understandings on the consistency and rationality of the pedestrian fall safety measurements. The key features of this book for the readers are to

- Identify major problems of the existing methodologies for the evaluation of pedestrian slip resistance properties;
- Understand friction and wear behaviours of shoes and floors and their interactive mechanisms involved at the sliding interface between them.
- Recognize the effects of floor surface finishes on slip resistance properties and determine design ideas with operational levels of floor surface roughness for optimal slip resistance performance under a range of slippery environments.

Construction of This Book

This book begins with a discussion on slip resistance measurements as a format of the coefficient of friction (COF), the most widely used definition and classification for fall safety assessment and their tribo-physical characteristics and consequences on slip resistance performance. Furthermore, this book provides in-depth overviews on friction mechanisms and suggests practical design recommendations for pedestrian walkway surfaces to prevent falls and fall-related incidence. The following areas are covered in each chapter:

Chapter 1
There have been sustained efforts to understand the main causes of slip and fall incidence in order to reduce their injuries and severities. It has been found that slip resistance performance between the footwear and underfoot surface is of great importance for preventing fall incidence and has been measured as a form of a coefficient of friction (COF). In this milieu, knowledge about friction demand and friction available has been recognized as the key factor in slip evaluation. Since the COF measurements at the sliding interface have been adopted to determine whether a slip is to occur, there has been ambiguity in the interpretation of COF measurement results. It has been found that any slip resistance measurement results have unique characteristics to a specific combination of the shoe-floor-contamination tested and constant changes during the tests. Hence, observing slip resistance properties with a simple friction measurements has obvious difficulty as an indicator for identifying fall hazards between the footwear and underfoot surfaces.

This chapter demonstrates that future research for the pedestrian fall prevention requires improving the validity and reliability of slip resistance measurements from an engineering point of view where principal understandings on the shoe-floor friction and wear behaviours can be made. This chapter also discusses that comprehensive investigations for the surface analyses of the shoes and floors with dynamic friction measurements are required to understand mechanical and physical behaviours of the shoe-floor friction and wear systems.

Chapter 2
Slip resistance property between the footwear and underfoot surface is of great importance for assessing slip and fall incidence and has been measured as a form of a coefficient of friction (COF). Hence, knowledge about friction demand and friction available has been recognized as a key factor to fall safety measures. Since the COF measurements at the sliding interface between the floor surface and shoe heel have been adopted to determine whether a slip is to occur, there has been ambiguity in the interpretation of the COF readings. The recent studies have found that any slip resistance measurements have (1) characteristics peculiar to a specific combination of the shoe-floor-environment measured and their interaction at the sliding interface, and (2) constantly varied during their service times. Hence, there is an inherent risk in relying upon a single COF result to provide an indication of the slip resistance properties between the shoe and floor surface.

In this sense, this chapter is focused on improving the validity and reliability of slip resistance measurements. To achieve this goal, the problem of slip resistance analysis has been approached by a tribo-physical point of view where a principal understanding on the floor-shoe friction mechanism can be made. This chapter also covers fundamental aspects of slip resistance properties and surface analyses for the floors and shoes with their mechanical and physical characteristics.

Chapter 3
As clearly deliberated in Chaps. 1 and 2, simple friction measurements could misrepresent accurate slip resistance properties between the shoe and floor. Facilitated routine friction measurements from laboratory environments could also oversimplify the intrinsic characteristics of slip resistance. Although there has been considerable progress in understanding the fundamental features of frictional behaviours of the shoes and floors, it is probably true to say that none of the COF measurements reported to date can be regarded as final objective values for a given shoe-floor-contaminant combination.

As long as the controversy around friction measurement as a format of COF remains, improvements in the principal concepts and methodologies on slip resistance measurements are urgently required. Therefore, this chapter principally focused on broadening the knowledge base and developing new ideas on which improvements in the validity and reliability of slip resistance measurements may be made.

Chapter 4
An adequate level of traction or slip resistance at the shoe-floor sliding interface is required for unperturbed ambulation. Without the presence of friction, ambulation could simply not occur. The classical model of friction defines slip resistance behaviours within simple parameters and is limited in its ability to explain the mechanics present at the shoe-floor sliding interface. In the context of human ambulation, however, friction is a complex phenomenon and contains multi-factorial mechanisms. Over time periods, the classical model of friction has developed into a paradigm which accounts for both human and environmental friction components; the relationship between them determines the propensity for a slip to occur.

However, as demonstrated above, surface topographies of both shoe and floor can be largely changed by friction-induced wear developments. As a result, this would significantly affect slip resistance properties. Therefore, surface finishes of the shoe and floor should be monitored routinely to maintain and provide the best slip resistance performance against specific walking/working environments.

This information may provide more reliable results to manage pedestrian fall safety than measuring slip resistance alone. Such approaches highlight the need for developing enhanced concepts and methods for reliably characterizing slip resistance properties. This should be based on thorough understanding of the complex nature of frictional behaviours between the shoe and floor surface, their related tribo-physical characteristics, and their interactive impacts on slip resistance performance.

Chapter 5
This chapter discusses the factors that affect slip resistance properties between the shoe heel and the floor surface. The factors are mainly classified into two components: adhesion and deformation in terms of frictional force. The contribution of the resultant frictional force totally depends on the various elements such as normal pressure, sliding force and surface texture. Amongst all these elements, however, the surface characteristics and their interactions are eventually major reasons to affect frictional and wear events of the sliding interface between the shoe outsole and floor surface. Because the surfaces of almost all solids are far from smooth under the microscopic view, even the surfaces of shoes and pedestrian floorings seem to have coarser and rougher surface features. It is, therefore, necessary to investigate the variations of surface characteristics with their friction and wear behaviours.

The above descriptions of the possible forms of friction and wear behaviours clearly demonstrated why it might never be possible to predict accurately their tribo-physical characteristics between two solid materials, particularly in the case of sliding friction between the shoe heel and floor surface. A systematic approach was discussed in which friction and wear processes between the shoe heel and floor surface during the prolonged sliding events were broken down into several elemental courses forming a feedback loop and a newly developed model for the wear mechanisms between the shoe and floor surface was suggested.

It is considered that theoretical developments for the shoe-floor contact surfaces and their tribo-physical characteristics have not yet reached a mature stage, where it would be possible quantitatively to predict friction and wear behaviours from known surface characteristics; but this would be a useful diagnostic tool and be a step forward to identify the complex issues. In this chapter, therefore, the origin of friction forces was examined and related tribo-physical features such as wear evolutions at the sliding interface between the shoe and floor surface were extensively explored. However, the discussion was mainly focused on understanding for the friction and wear behaviours of unlubricated solids in sliding motions as a first instance.

Chapter 6
The measurement and interpretation of slip resistance properties should be based on full understanding of the relevant tribo-physical characteristics and involved mechanisms as an essential prerequisite because the friction measurement amongst the shoe, floor and environment are not a simple matter. In this sense, it would be a constructive attempt to study the topographic features of surfaces, their contact-sliding mechanisms and related tribo-physical behaviours. In order to recognize tribological processes involved at the sliding interface between the shoe and the floor surface, this chapter discusses how the two surfaces interact when they are loaded together. Surface analyses and relevant background information were comprehensively reviewed with different measuring instruments to quantify topographic aspects of the shoe and floor surfaces.

Several geometrical models were comprehensively reviewed and related theoretical issues were also carefully discussed. The concept on changes in surface topographies of two interacting bodies as a result of sliding friction actions was applied to the sliding interface between the shoe and floor. Based on the main assumptions with thorough knowledge foundations for the contact-sliding mechanisms between two surfaces, a theory model on the contact-sliding mechanism between the shoe heel and the floor surface was suggested. A perfect contact-sliding model to predict slip resistance performance between the shoe and the floor surface has not been developed yet, but tribological approaches seem to be a worthwhile attempt to overcome limitations on the existing researches and practices for the measurements of pedestrian fall safety.

Chapter 7
Increasing traction properties of the floor surface would be desirable as a general rule, but a very high level of slip resistance may impede safe and comfortable ambulation. There is a lack of evidence whether traction properties are linearly correlated with surface features of the floor or what levels of floor surface finishes are required to effective control of slipperiness. It is also scarce to find studies and/or guidelines on the operational ranges of floor surface roughness required for optimal slip resistance performance.

The main objectives of this chapter are to investigate the effects of floor surface finishes on slip resistance performance under different environmental and shoe-type conditions and identify operational ranges of floor surface roughness as practical design information for the effective control of fall incidents. A theory model of three operative zones was suggested to characterize functional levels of floor surface roughness on slip resistance performance. To test the theory model, dynamic friction tests were conducted using 3 shoes and 9 floor specimens under 4 different environments: clean and dry, wet, soapy and oily conditions. The test results showed that significant effects of floor-type on DFCs were found in the polluted environments. As compared to the floor-type effect, the shoe-type effect was relatively small. Slip resistance performance was significantly affected by and well correlated with the floor surface roughness under the soapy and oily environments. Polynomial regression analyses amongst the floor surface roughness, DFCs and environments allowed to estimating operational ranges for optimal slip resistance performance.

Floor surfaces with around 17 μm to 52 μm and 35 μm to 52 μm in $\boldsymbol{R_a}$ roughness parameter most likely represented the lower and upper bounds of operational ranges for the best slip resistance managements under the soapy and oily surface conditions, respectively. The test result also identified that the oily environment required twice rougher floor surface than the soapy one in their lower boundary roughness scales: 35 μm vs. 17 μm in $\boldsymbol{R_a}$ roughness parameter. On the other hand, the upper bound of floor surface roughness showed the same ranges of surface roughness scales: 52 μm in $\boldsymbol{R_a}$, 300 μm in $\boldsymbol{R_t}$, and 180 μm in $\boldsymbol{R_{tm}}$ roughness parameters under the three lubricated environments. However, there was a lack of correlations between the surface roughness and slip resistance properties under the clean and dry and wet surface conditions.

The inclusive results from this chapter also clearly display that the proposed concept on the operational ranges for the floor surface roughness may have practical design implications for floors and floor coverings to reduce slip and fall hazards.

Chapter 8
This chapter suggests recommendations for the future studies of pedestrian fall incidents and their investigations, measurements, interpretations and prevention strategies. Specifically, this chapter suggests that physical accuracy and validity of the developed shoe-floor-environment sliding friction model need to be improved and expanded to include a diverse range of shoes, floor types and environmental conditions. The chapter proposes exclusive ideas on how the future generation of tribo-physical model(s) for the shoe-floor-environment can be further improved to become a useful tool(s) for the prevention of slip and fall incidence.

Final Remarks

As a researcher in this field, I am honoured to be writing a book with such a fascinating and exciting topic. I would like to thank the reviewers, who have committed so much towards the publication of this work. Without their invaluable reviews, this book could not have been written.

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