EXPERIMENTAL EVIDENCE ON WEAR BEHAVIOURS OF FLOOR SURFACES AND AN APPLICATION FOR SLIP AND FALL SAFETY ASSESSMENTS

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Flooring materials and floor coverings should retain continual slip resistance qualities throughout lifetime, but their slip-resistance properties could be changed over time. Those variations seem to largely affect slip resistance performance. Main aims of this study are to 1) determine if there are significant differences in the measured slip-resistance properties of floor surfaces, 2) identify wear effects of floor surfaces on slip-resistance performance, and 3) formulate a clear concept on wear phenomena of the floor surfaces. To approach the aims, dynamic friction tests were conducted amongst3 different types of floor specimens with a similar range of topographic characteristics and two shoes under a clean and dry condition. Topographic changes and wear developments of each floor surface were quantitatively and qualitatively measured by surface roughness parameters and microscopic observations. Findings from this study clearly showed that initial surface features of the floor specimens were clearly modified during an early stage of dynamic friction tests and significantly affected slip-resistance properties. Results also identified that various regimes of wear behaviours such as adhesive, abrasive, ploughing, and fatigue were found as main wear behaviours and the resultant effects on slip resistance performance. This study suggests that future research on slips and falls should pay a close attention to the issues on relevant wear phenomena of the floor surfaces and their effects on slip-resistance performance.

Introduction

Fall incidents resulting from slips are the major outcomes in surveys on serious occupational incidents as well as one of the most common geriatric syndromes threatening the independence of older people (Dias *et al.*, 2011; Perez-Jara *et al.*, 2012; Demura *et al.*, 2013; Whitney *et al.*, 2013). Although many factors contribute to slips and falls, underfoot surfaces and floors have a major effect on the incidents. Floors and underfoot surfaces should be constructed to provide comfortable walking environments and good protection against any slip potentials. With continued walking activities, however, topographic changes and progressive wear of the floor surfaces are unavoidable and they can substantially affect slip-resistance properties.

Changes of surface topographies of the floors during slip-resistance measurements have been reported in the recent literature. For example, extended wear on smooth floors could cause polishing effects and considerable drops on coefficient of friction (COF) quantities (Manning *et al.*, 1998; Kim & Smith, 2000, 2003; Kim *et al.*, 2001; Kim, 2004a, 2004b). Those studies showed strong relationships between surface roughness and slip-resistance properties, but fundamental aspects on wear phenomena and associated tribological characteristics of the floor surfaces were not fully explored. In particular, it is scarce to find any definitive concepts and methodical studies on wear behaviors of the floor surfaces and their effects on slip-resistance performance. The present study aimed to:

(1) perceive fundamental aspects of wear behaviors of the floor surfaces;
(2) understand the nature of surface changes and wear developments of the floor surfaces; and
(3) identify their effects on slip-resistance performance.

To validate such aims, topographic characteristics of new and rubbed floor specimens were measured by a number of surface roughness parameters before and after slip-resistance tests for quantitative analyses. A series of micrographs were also taken by a scanning electron microscope to monitor surface changes and wear growths of the floor specimens after the tests for qualitative analyses.

Material and methods

Dynamic friction tester

A pendulum-type hydraulic dynamic friction tester was used to measure slip-resistance properties. The tester's set up values could be adjusted to cover various parameters taken from human walking trials such as a heel contact angle, vertical load and its rate of increase and sliding speed. The normal force was kept around 400 N and the sliding speed was controlled at 25 cm/sec based on gait studies (Kim *et al.*, 2013). A heel contact angle of 9º was chosen by the result of previous biomechanical studies (Kim *et al.*, 2013).

Floor specimens

In order to objectively monitor changes on surface topographies of the floor specimens and analyse their effects on slip-resistance performance, 3 different types of floor specimens: vinyl, terracotta, and ceramic with a similar range of topographic characteristics were used (see, Table 1). The floor specimens were thoroughly cleaned with demineralised water to remove any dirt and dust, dried and kept in plastic containers during the tests.

Table 1. Summary of surface roughness parameters of floor specimens before (BFT) and after the tests (AFT)

Surface Roughness Parameters	Vinyl		Terracotta		Ceramic	
	BFT	AFT	BFT	AFT	BFT	AFT
Ra	2.330	1.477	2.788	2.727	3.933	1.986
Rq	3.121	1.973	3.767	3.355	4.935	2.571
Rtm	16.817	15.860	19.008	10.599	19.500	9.900
Rpm	6.483	4.882	11.701	5.192	10.899	5.827
Rvm	-7.492	-3.645	-7.307	-5.407	-8.601	-4.073

Shoes

New Nitrile Rubber (No. 1) and Polyurethane (No. 2) soled shoes were used. The shoes were thoroughly cleaned with demineralised water to eliminate any dirt and dust, dried and kept in plastic containers during the tests.

Test conditions

Dynamic friction tests were conducted on clean and dry conditions in order to eliminate any confounding effects of contaminants by agents other than shoe and floor specimens themselves. The controlled test conditions were also intended to investigate the following two major goals:

1) observe dominant effects of geometric characteristics and wear behaviours of the floor specimens such as wear formation, growth and propagation; and
2) investigate main roles of surface topographies of the floor surfaces and their effects on slip-resistance properties.

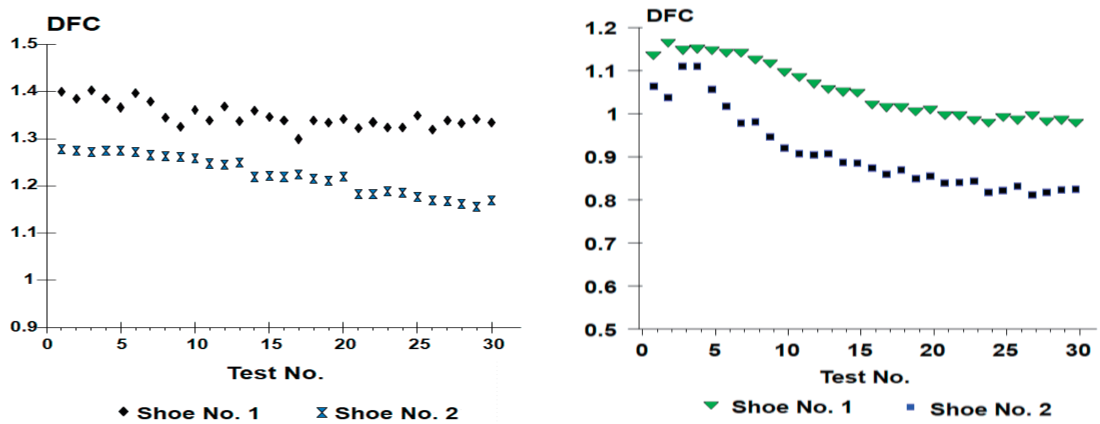
Quantitative analysis
A laser scanning confocal microscope (MRC-600, Bio-Rad) which had 0.1 μm step size was used to measure surface roughness of the floor specimens before and after the tests. Surface profiles of the floor specimens were measured three times at five different locations along the sliding directions. Averages of the individual roughness measures were used for the analysis.

Peak height related roughness parameters such as *Rtm*, *Rpm*, and *Rvm* were measured with surface height ones such as *Ra* and *Rq* before and after the tests. Details of the surface roughness parameters are found in the literature (Kim & Smith, 2000; Chang *et al.*, 2001).

Qualitative analysis
In order to validate surface roughness data and identify wear modes and developments, rubbed surfaces of the floor specimens were comprehensively examined by a stereo scanning electron microscope (SEM: XL 30, Philips). The SEM was operated at 10 kV setting to avoid radiation damages to the transferred polymeric particles from the heel surface.

Results

Slip-resistance performances
Fig. 1 shows the result of dynamic friction tests between the three floor specimens and two shoes. Quantities of dynamic friction coefficient (DFC) were largely decreased after the tests. In the case of the Polyurethane shoe (Shoe No. 2), the DFC values showed larger changes than the Nitrile Rubber one (Shoe No. 1) rubbed against all the three floors.



(a) Vinyl floor (b) Terracotta and Ceramic floors

Figure 1. Results of dynamic friction tests amongst three floor specimens and two shoes under clean and dry surface conditions: (a) Vinyl floor and (b) Terracotta and Ceramic

Surface analysis - Quantitative approach

Surface roughness parameters
Table 1 summarizes the measurement results of surface roughness parameters of each floor specimen after the tests. As shown in Table 1, all the roughness parameters of the floor specimens were largely changed after the dynamic friction tests. The detailed observations on each roughness parameter are further discussed in the below:

(1) Centre-line average (*Ra*) and root mean square (*Rq*) roughness parameters

Ra and *Rq* parameters of each floor surface were largely decreased by about 36.61%, 2.19%, and 49.50% in *Ra*, and 36.78%, 10.94%, and 47.90% in *Rq*, respectively after the tests. These seemed to be caused by depositions of polymeric materials from heel surfaces into discrete patches of the floor surfaces. As a result, modified roughness heights directly contributed to the roughness parameters.

(2) Maximum mean peak-to-valley (*Rtm*) and maximum mean peak height (*Rpm*) parameters
Rtm and *Rpm* parameters of each floor surface were also largely decreased by about 5.69%, 44.24%, and 49.23% in *Rtm*, and 24.70%, 55.63%, and 46.54% in *Rpm*, respectively after the tests. These findings showed a strong evidence of the flooring wear as a direct wear progress.

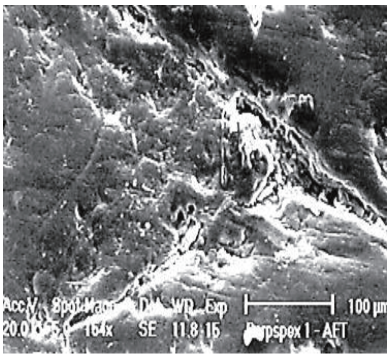
(3) Maximum mean depth (*Rvm*) parameter
Rvm parameter of each floor surface was significantly reduced by 51.35%, 26.00%, and 52.65%, respectively after the tests. This reduction showed the largest changes amongst the measured roughness parameters. This result identified that polymeric wear debris and particles from the heel surfaces were largely embedded into valley areas of the floor surfaces. This finding suggests a clear evidence of the flooring wear as an indirect wear progress.

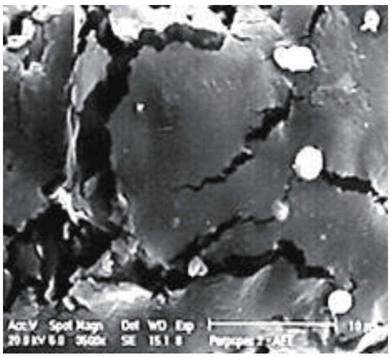
Surface analysis - Qualitative approach

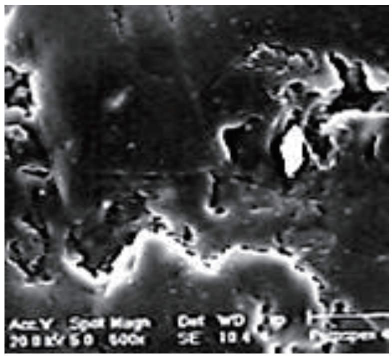
Wear observations

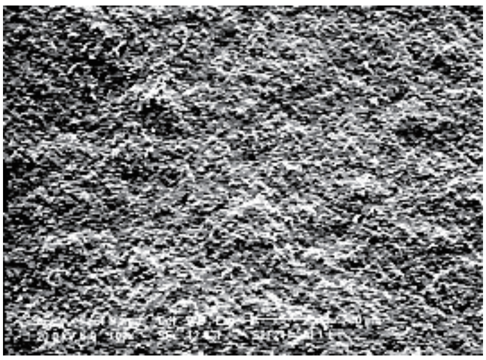
Fig. 8 shows examples of micrographs of the floor surfaces rubbed against the two shoes after the tests. Each floor experienced extensive wear events during the tests. A range of wear particles and debris with different patterns, shapes and sizes were found on the floor surfaces.

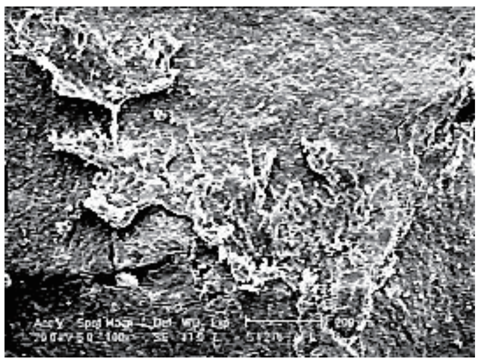
Those findings provided visible evidences of the flooring wear as a function of direct material transfer. The greater the roughness of the floor surface the wider the ranges and shapes of wear particles. The main findings on wear modes of the floor surfaces are summarized in the following:

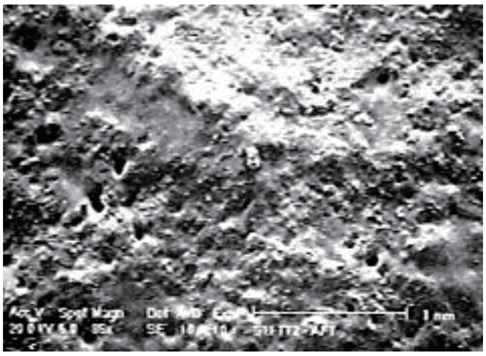

(a) Vinyl floor – BFT


(b) Vinyl floor vs. Shoe No. 1


(c) Vinyl floor vs. Shoe No. 2


(d) Terracotta – BFT


(e) Terracotta floor vs. Shoe No 1



(f) Ceramic floor – BFT

(g) Ceramic floor vs. Shoe No. 2

Figure 2. Micrographs of the floor surfaces rubbed against two different shoes – BFT and AFT

(1) Large amount of wear debris and particles were observed on the surfaces of wear tracks, depending upon the topographies of floor surfaces;
(2) Different shapes, sizes, and types of wear debris were embedded into the valley areas of the floor surfaces;
(3) Wear evolutions were generally associated with the nominal contact areas between the floor surfaces and the shoe heels; and
(4) Irregular shaped fragments were commonly found in the wedge areas, but the transferred wear particles did not heavily cover the peak asperities of the floor surfaces.

Limitations of the study

This study tested only a small selection of flooring materials within a limited number and range of surface roughness scales. Further research on the slip resistance properties of a range of flooring materials with different surface characteristics is needed to comprehensively understand flooring wear mechanics and mechanisms. Experimental design of this study involved only clean and dry surface conditions. This limits the applicability of findings from the current study only to this type of surface condition. Other surface conditions such as lubricants and contaminants with different composition and viscosity may result in different phenomena of flooring wear.

Conclusion

This study aimed at understanding wear behaviors of the floor surfaces in an early stage of simulated slip resistance measurements and identifying their effects on slip-resistance properties. A series of dynamic friction tests were conducted amongst three common types of floor specimens and two shoes under clean and dry conditions. The rubbed surfaces of each floor specimen were comprehensively analyzed by quantitative and qualitative methods. From the overall results, the followings main findings were summarized:

1) There were significant changes in the topographic structures of the floor specimens after the tests. Topographic structures of the floor specimens were largely altered not only in the initial stages, but also in the later stages of slip resistance tests by wear-induced sliding friction processes.
2) Surface roughness parameters of each floor specimen showed large variations after the tests. Amongst the measured surface roughness parameters, the maximum mean peak height (*Rpm*) and maximum mean depth (*Rvm*) of all the floor specimens underwent significant changes (on average more than 42% for *Rpm* and 43% for *Rvm*, respectively) after the tests.
3) Wear developments of the floor specimens were caused by a combination of direct material transfer from the shoe heels and indirect abrasive wear evolutions of the floor specimens.

4) Structural changes of the floor surfaces directly affected to DFC results.

Overall outcomes from this study clearly showed the importance of flooring wear phenomena and their significance effects on slip-resistance properties. It is wished that the idea explored in this study may not only provide a sound foundation for the understanding of wear phenomena of the floor surfaces but also make a progress towards an account of the underlying complex mechanisms of slip-resistance properties.

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