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Development of new footwear sole surface pattern for prevention of slip-related falls

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ABSTRACT

In this study, a new rubber surface pattern for a footwear sole was developed to prevent slip-related falls. This pattern shows a high static coefficient of friction (SCOF) and a high dynamic coefficient of friction (DCOF) when sliding against a liquid contaminated surface. A hybrid rubber block, in which a rubber block with a rough surface (Ra = 30.4 μm) was sandwiched between two rubber blocks with smooth surfaces (Ra = 0.98 μm), was prepared. The ratio of the rough surface area to the whole rubber block surface area *r* was 0%, 30%, 50%, 80%, and 100%. The coefficient of friction of the rubber blocks was measured when sliding against a stainless steel plate with Ra of 0.09 μm contaminated with a 90% aqueous solution of glycerol. While the SCOF increased with an increase of the rough surface area ratio *r*, the DCOF during steady-state sliding decreased with an increase of the rough surface area ratio *r*. The rough surface area ratio of 50% achieved a SCOF value around 0.5 or more and a DCOF value greater than 0.5. Furthermore, the difference in the value of the SCOF and DCOF was the smallest for the rubber block with *r* of 50%. The results indicated that the rubber block with *r* of 50% would be applicable to a footwear sole surface pattern to prevent slip and fall accidents on contaminated surfaces.

1. Introduction

The number of slip and fall incidents in occupational accidents has been increasing in Japan as well as in other industrialized countries. (Ministry of Health, Labor and Welfare, 2006; Courtney et al., 2001; Courtney and Webster, 2001). Most slip and fall accidents in the workplace occur on liquid contaminated floor surfaces (Strandberg, 1985; Proctor and Coleman, 1988; Grönqvist, 1995; Leclercq et al., 1995; Manning and Jones, 2001). Such smooth floor surface is slippery when contaminated with water or oil due to the formation of a fluid film in the contact interface between the footwear sole and the floor. Thus, a footwear sole pattern with a high slip-resistance, even on such slippery surface, is required to prevent slip-related falls.

The coefficient of friction is often used for the evaluation of the slip resistance of a footwear sole. There have been controversies in selecting either static friction or dynamic friction as the critical frictional parameter at the contact interface between the footwear sole and the floor for the prevention of slip-related falls (Ekkubus and Killey, 1973; Tisserand, 1985; Pilla, 2003; Yamaguchi and Hokkirigawa, 2008). As Perkins (1978) pointed out, slip velocity and slip distance, which both have a strong correlation with a fall due to induced slip, increase with the difference of the values of static coefficient of friction (SCOF) and dynamic coefficient of friction (DCOF). In particular, if the SCOF is high but the DCOF was very low, slippage may not be stopped when the required coefficient of friction (RCOF) reaches the SCOF, resulting in slip initiation. On the other hand, if the SCOF is small enough for slip to occur but the DCOF is high, slippage stops and a fall will be avoided. Therefore, it has recently been considered that the DCOF is a more relevant measurement from slip biomechanics studies (Strandberg and Lanshammar, 1981; Perkins and Wilson, 1983; Strandberg, 1983; Grönqvist et al., 1989), and it is insufficient to evaluate the slip-resistance of shoe soles and floors only with the value of SCOF. However, if we have a shoe sole pattern which provides sufficiently high SCOF and DCOF, it would be safer because it helps to prevent slip initiation and to stop slip even if it occurs. The safe limit of DCOF for walking on level floor was suggested to be 0.20–0.40 by various studies (Grönqvist et al., 1989, 2003; Redfern and Bidanda, 1994; Strandberg, 1983). Fong et al. (2009) reported that humans walk carefully to avoid slipping when the DCOF drops below 0.41. Grönqvist et al. (2003) suggested that the limit for preventing a slip was in the range 0.3–0.35, and if the DCOF was below this limit, a person would change their gait to adapt to the slippery surface. Nagata et al. (2009) also suggested that the fall risk due

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to induced slip increased when the coefficient of friction was below 0.4 based on a ramp test. Therefore, values of SCOF and DCOF greater than 0.4 would be required for the shoe sole/floor interface. However, too high friction could introduce tripping, and it is difficult to determine the upper limits of DCOF and SCOF to prevent this occurring.

The velocity of the slipping foot, which is also believed to be one of the determinants of whether an induced slip will result in the fall or the postural recovery (Perkins, 1978; Perkins and Wilson, 1983; James, 1990), is a function of the difference between the values of SCOF and DCOF (Tisserand, 1985). Thus, reduction in the difference between these values would also be one of the critical frictional properties between the footwear sole and the floor.

According to Bowen and Tabor (1950), friction force is a sum of an adhesive friction term (F_{adh}) and a deformation friction term (F_{def}), as given by

$$F = F_{adh} + F_{def} \tag{1}$$

Adhesive friction results from the contact and subsequent shearing of individual surface asperities; and the deformation component is due to the ploughing or other forms of deformation caused by the harder surface on the softer surface. When a rubber slides on a smooth harder surface, the ploughing effect can be neglected. Hence the adhesive friction is directly proportional to the real area of contact and is given by

$$F = \tau A_r \tag{2}$$

where τ is the interfacial shear strength of the contact and A_r is the real area of contact.

The elastic modulus of rubber, usually used as footwear sole material, is low compared to other engineering materials. Hence, a high real area of contact between mating surfaces provides high values of static and dynamic friction under dry conditions. However, when sliding against a smooth surface contaminated with water or oil, a fluid film may be formed at the contact interface. The interfacial shear strength is determined by the fluid film, which results in low values of static and dynamic friction. Therefore, increasing the amount of contact area between the rubber and the mating surface by removing the fluid film is important to increase the coefficient of friction under lubricated conditions.

The slip resistance, i.e. coefficient of friction, of shoe soles with various tread pattern (macroscopic pattern) and surface roughness (microscopic pattern) characteristics has been measured on contaminated floors (Grönqvist, 1995; Grönqvist et al., 1999; Wilson, 1990; Chang et al., 2001a; Li and Chen, 2004, 2005). These studies indicated that the surface roughness and tread pattern of the shoe sole are helpful for liquid drainage to increase the coefficient of friction. Hence the surface pattern design of a rubber sole, including tread pattern and surface roughness, is of great importance in improving slip-resistance. However, adequate design criteria (guidelines) for a shoe sole pattern with sufficient slip resistance on contaminated surfaces have not been fully understood. Therefore, the surface pattern design of the footwear sole required to increase SCOF and DCOF on contaminated surfaces is unclear.

In this study, a new rubber surface pattern for footwear soles using a hybrid rubber block combining smooth and rough surfaces, which showed sufficiently high SCOF and DCOF when slid against a liquid contaminated surface, was developed. The mechanisms of the increased SCOF and DCOF of the hybrid rubber block were also investigated based on the contact area measurement between the rubber block surface and the counterpart material surface by use of total reflection of light.

2. Methods

2.1. Sample preparation

NBR (acrylonitrile butadiene rubber) was formed into a rectangular block geometry (25 mm × 25 mm × 5 mm) using two kinds of metallic molds with different surface roughness. The tensile strength of the NBR was 9.52 MPa, the elongation was 875%, the 300% modulus was 1.12 MPa, and the shore hardness (A/15) was 45. The surface roughness Ra of each rubber block was 0.98 μm (smooth surface) or 30.4 μm (rough surface). The hybrid rubber blocks, in which a rubber block with a rough surface was sandwiched between rubber blocks of the same size but a smooth surface, were prepared as shown in Fig. 1a and b. The rubber blocks were adhered with a modified silicon adhesive. The rough surface area ratio r was defined as following formula;

$$r = \frac{a}{25} \times 100\ [\%] \tag{3}$$

where a is length of the rubber block with a rough surface in the sliding direction (mm). Rubber blocks with rough surface area ratio r values of 0%, 30%, 50%, 80%, and 100% were prepared. Fig. 1c shows the topography of the rubber blocks (surface profile curves), which was measured with a contact type stylus profiler (Poon and Bhushan, 1995). The stylus was loaded on the surface to be measured and then moved across the surface along the sliding direction of the friction test at a constant velocity, to obtain surface height variation.

2.2. Experimental setup

In this study, the following two kinds of friction test were carried out using a reciprocating linear sliding type tribo-meter (SHINTO Scientific Co., Ltd.). The friction tests of the rubber blocks were conducted on a polished stainless steel plate (JIS SU304) and a polished glass plate. Stainless steel with smooth surface is commonly used as a floor material in food processing plants, where sanitary control is valued, from the viewpoint of ease of cleaning. Therefore, a polished stainless steel plate was used as one of the mating materials. On the other hand, the friction tests on a polished glass plate were conducted in order to measure the contact area between the rubber block sample and the mating surface and discuss its effect on the coefficients of friction by using the total reflection of light.

2.2.1. Friction test sliding against a polished stainless steel plate

Fig. 2 shows a schematic diagram of the experimental setup for the friction tests between the rubber block and the polished stainless steel plate. The rubber block sample glued on the base rubber block (the same NBR, 30 mm × 30 mm × 20 mm) was affixed on the sample holder. The rubber block was slid against the stainless steel plate (500 mm × 60 mm × 1 mm) with surface roughness Ra of 0.09 μm mounted on a linear motion stage. The linear motion stage was driven by a servo-motor through a ball screw. A normal load was applied by a 56.6 N dead weight. Friction force was measured with a push–pull type force gauge, and the friction force data were recorded by a digital data logger. The coefficient of friction was calculated by dividing the friction force by the normal load. The SCOF was the coefficient of friction at the time when a macroscopic slip occurred between rubber block and the mating stainless steel plate, which was determined by observation of the contact interface viewed from the side with a high speed camera (MotionPro X3, IDT Japan, Inc.). The steady-state DCOF was taken as the mean value of the coefficient of friction while the stage velocity (sliding velocity) was constant.