1. Introduction

Unpredictable falls are one of the most significant factors that prevent elderly people from independent daily activities [1]. The incidence rate of falls tends to increase rapidly with age, with a third of elderly people aged 65 and over [2]. The annual direct cost of fall-related workers’ compensation alone is estimated to be about $6 billion in the US [3]. The slip-related falls (SRFs) are found to be involved in 40–50% of fall-related injuries [3]. The prevention of SRFs is an important solution to prolong healthy life expectancy.

The three types of analysis systems have been developed for clarifying the mechanism of SRFs: force plate systems, video analysis, and sensor-embedded shoe systems. Yamaguchi et al. evaluated the mechanism of SRFs in elderly people during turning steps by analysing the required coefficient of friction utilizing force plates and video [4]. In contrast, sensor-embedded shoe systems play an important role to investigate factors of SRFs in various aspect of daily activities. Capacitive, piezoresistive [5], optical [6], micro-electromechanical systems (MEMS)-based [7], and triboelectric [8] sensors are embedded in shoes and insoles. All of these shoes are designed for gait analysis or detecting falls. Few studies have focused on slip detection for preventing from SRFs [9] but the system includes heavy and complex sensor modules.

The slip detection sensors are broadly classified into three categories; vibration sensors, pressure distribution sensors, and incipient slip detection sensors [10]. Among them, an incipient slip detection sensor is a crucial candidate because the sensor prevents the SRFs in advance. Incipient slip is the partial slip phenomenon that occurs before the global slip. Okatani et al. utilized the phenomenon and expand the detection method to measure the static coefficient of friction (SCOF) using MEMS piezoresistive beams [11]. Then, he integrated a triaxial force sensor or a six-axial force/torque sensor into the SCOF sensor and fabricated a multifunctional slip detection sensor [12, 13]. Merely by pressing the sensor against an object, the sensor detects the strain of the elastomer and estimate SCOF.

Here, the peripheral local slips (PLSs) detection via elastic hemisphere (Figure 1) is focused on because of the similarity of incipient slip. When a normal force is applied to the elastic hemisphere from a flat rigid body and the contact area is sufficiently large [14], the difference in SCOF affects the PLSs on the contact area. When the SCOF is larger (smaller), the contact area becomes smaller (larger) by the PLSs, which causes the larger (smaller) the maximum central pressure ($P_{\text{MAX}}$) of the elastic hemisphere. In short, the change of the SCOF is estimated by measuring $P_{\text{MAX}}$ in the elastic hemisphere. In this study, we demonstrate that a one-axis force sensor with an elastic hemisphere for measuring $P_{\text{MAX}}$ can detect slip in advance. To investigate the design guidelines of the sensor, we experimentally
evaluated the Young's modulus of the elastic hemisphere and the ratio of the hemisphere diameter to the one-axis force sensor diameter. The sensor must be small enough to fit comfortably for users and measured in the response pressure range (from 10 to 175 kPa) of plantar pressure [15].

The structure of this paper is as follows. First, the experimental configuration that measures $P_{\text{MAX}}$ and SCOF is described. Then, the relationship between $P_{\text{MAX}}$ and total normal force ($F_{\text{TOTAL}}$) is evaluated using two different Young's modulus elastomers. Next, the $F_{\text{TOTAL}}$ dependence of $P_{\text{MAX}}$ and SCOF is pointed out and the effect of the different interface conditions on the contact pressure is mentioned. Finally, the diameter of the one-axis force sensor ($\phi_s$) is compared with the diameter of the elastic hemisphere ($\phi_e$), and the limitation of the $\phi_s/\phi_e$ ratio is displayed.

2. Experimental configuration

2.1. Fabrication of elastic hemispheres

In order to investigate the effects of several Young's modulus ($E$) and radius of curvature, elastic hemispheres were fabricated. Ecoflex (Smooth-on, 00-30A, $E = 45 \pm 11$ kPa) and polydimethylsiloxane (PDMS; TORAY, SILPOT 184, Base : catalyst = 10 : 1, $E = 1.6 \pm 0.4$ MPa) solutions were degassed and poured into hemisphere silicone moulds. The diameters $\phi_e$ were 12, 18, 24, and 30 mm. The moulds were annealed at 70 °C for 2 h and waited for an hour at room temperature. The elastic hemispheres successfully peeled off the moulds.

To measure the surface roughness of the fabricated elastic hemispheres, the arithmetic mean roughness ($R_a$) of the Ecoflex at 12, 18, and 30 mm was measured using a 3-D laser confocal microscope (Keyence Corp.). The surface profile after the spherical fitting is shown in Figure 2. The $R_a$ of the Ecoflex at 12, 18, 24 and 30 mm is 0.67, 0.42, 0.66 and 0.34 mm, respectively. Smooth surfaces were successfully fabricated.

2.2. Sensor structure

The fabricated elastic hemispheres were attached on an aluminium plate. The plate was connected to a digital force gauge (ZTA-50N, IMADA Co., Ltd.) through the hole drilled with around 6.1 mm at the centre (Figure 3). The $\phi_e$ was 6.0 mm and aluminium plate and the end of the force gauge were completely flat to attach the elastic hemispheres seamlessly. Instant adhesive and strong double-sided tapes (No.5000NS, Nitto Denko Corp.) were utilized between aluminium plate and hemisphere.

2.3. $P_{\text{MAX}}$ measurement setup

A measurement system for the $P_{\text{MAX}}$ of the elastic hemisphere has been constructed (Figures 4 (a) and
Figure 3. The lateral view of the proposed sensor structure.

Figure 4. (a) Front view of measurement system, (b) Top view of measurement system. For \( P_{\text{MAX}} \) measurement, the test gauge pushes up the force gauge in the negative \( z \)-axis direction. For the shear force measurement, automatic motor pushes another force gauge in the \( x \)-axis direction, and the force gauge displaces the acrylic plate.

5 (a)). The force gauge attached to the elastic hemisphere was mounted on the vertical motorized test stand (MX2-500N, IMADA Co., Ltd.). Four stainless steel poles were attached to contact vertically between an acrylic plate and the elastic hemisphere. Low friction pillow blocks (MDBAC10, MISUMI Group Inc.) were set in the steel poles to reduce the effect of friction during weight sweeping. Constant weights were utilized to separate the \( F_{\text{TOTAL}} \) from the effect of the interface phenomena. The motorized test stand was operated in the negative \( z \)-axis direction at a speed of 300 mm/min and lifted the weights and objects. After waiting for 30 s, \( P_{\text{MAX}} \) was measured in different weights (5, 10, 15, 20, 25, 35, 45, 55, and 65 N) and different surface conditions; acrylic plate, polyethylene powder (MIPELON, Mitsui Chemicals, Inc.) and silicone oil (KF-961,000CS, Shin-Etsu Chemical Co., Ltd). The powder and oil were applied from below to the acrylic plate in Figure 5(a).

2.4. Shear force measurement setup

In order to measure the SCOF, we also constructed a shear force measurement system (Figures 4(b) and 5(b)). The pillow blocks were mounted horizontally on the stainless steel pole for fixing the acrylic plate. The acrylic plate is pushed by a force gauge fixed horizontally on an \( x \)-axis movable stage. The force gauge is pushed by an automatic motor (KDS100, kd Scientific) in \( x \)-axis direction at a speed of 12 mm/min. In order to investigate the actual \( x \)-axis displacement of the acrylic plate, we confirmed that the plate was displaced at the same speed as the automatic motor by using a video camera.

In order to investigate the SCOF measurement in the constructed system, a preliminary experiment of shear force was carried out using a 30 mm PDMS hemisphere (Figure 6). As soon as shear force was applied, the first peak of the shear force waveform was observed. This is the system-specific SCOF resulting from the movement of the pillow block referred to in Figure 5 (b). As time passes, the shear force reaches a second peak, and oscillatory behaviour occurs. This behaviour is considered to be due to the stick–slip between the elastic hemisphere and the flat plate. The SCOF is calculated as below;

\[
\text{SCOF} = \frac{F_{X-\text{MAX}} - F_{\text{TOTAL}}}{F_{\text{TOTAL}}} 
\] (1)

Figure 5. The schematic illustration of measurement systems about (a) \( P_{\text{MAX}} \) and (b) shear force.

Figure 6. The measured shear force of PDMS hemisphere (30 mm) at \( F_{\text{TOTAL}} = 35N \). Since the pillow block has a slight SCOF, the system itself has a system-specific slip phenomenon.
Where $F_{X-MAX}$ is maximum of shear force. Therefore, the $F_{X-MAX}$ cannot be measured unless it is larger than the first peek.

For an investigation of the SCOF of pillow block on the measurement system, we confirmed the system-specific friction without contact with the hemisphere (Figure 7). In this measurement system, SCOF could be detected quantitatively in the range of $SCOF > 0.1$ and $F_{TOTAL} > 7.5 \text{ N}$. Here, SCOF is the average of five times measurements. The different three types of surface states (acrylic plate, polyethylene powder, silicone oil) were also utilized the same as the $P_{MAX}$ measurement.

3. Experimental results and discussion

3.1. The Young’s modulus comparison on $P_{MAX}$ measurement

$P_{MAX}$ of PDMS hemisphere with 30 mm diameter was measured (Figure 8). The reason why the 30 mm is chosen is that the larger diameter means the more sensitive detection of the $P_{MAX}$. About a tenth of the weight of $F_{TOTAL}$ is applied to $P_{MAX}$. Despite the three different interface conditions, the behaviour of $P_{MAX}$ did not change and nearly identical outputs were measured. Next, $P_{MAX}$ of Ecoflex hemisphere with 30 mm diameter was measured (Figure 9). A clear difference is detected in $P_{MAX}$ for the three interface conditions when the $F_{TOTAL}$ is more than 7.5 N. Due to the low Young’s modulus of Ecoflex, the contact area of the Ecoflex hemisphere becomes larger than the PDMS hemisphere. As a result, the $P_{MAX}$ of Ecoflex tends to be lower than the $P_{MAX}$ of PDMS.

To compare with the differences in $P_{MAX}$ response between PDMS and Ecoflex, we checked the deformation of them. As shown in the inset of Figure 8, the PDMS hemisphere deforms a little and is hard to detect the PRSs. On the other hand, the inset of Figure 9 shows that the Ecoflex hemisphere deforms more largely than PDMS one. According to Xydas, when the radius of the contact area surpasses half of the radius curvature of the hemisphere, the interface friction affects $P_{MAX}$ [14]. In other words, large deformation makes the proposed sensor more sensitive to different surface situations. These results insist that the $P_{MAX}$ has an important role to estimate the SCOF.

In the next subsection, we quantitatively and qualitatively investigate the relationship between PDMS and Ecoflex by measuring SCOF.

3.2. The experimental validity of SCOF and $P_{MAX}$

Figure 10 shows the results of SCOF measurements for PDMS and Ecoflex at three different interface conditions. It is difficult to measure the SCOF of the oil quantitatively because the SCOF of the oil is smaller than the measurement-specific SCOF. At all interfaces, the SCOF decreases with increasing weight. This is typical behaviour for soft matter friction, which no longer obeys Amonton’s law [16]. Furthermore, according to Schallamach [16], the frictional force of rubber depends

Figure 7. The SCOF of pillow blocks for the system-specific limitation. Error bar means the s. d. of 5 times measurements. Tinted area is suitable on this measurement.

Figure 8. The measured $P_{MAX}$ of PDMS hemisphere (30 mm diameter). Error bar means the s. d. of 3 times measurements.

Figure 9. The measured $P_{MAX}$ of Ecoflex hemisphere (30 mm diameter). Error bar means the s. d. of 3 times measurements.
on the true area of contact. Therefore, the Ecoflex hemisphere, which causes larger deformation than PDMS, has a larger contact area and a smaller SCOF.

To understand the relationship between SCOF and $P_{\text{MAX}}$, Figure 10 is compared with Figures 8 and 9. There is no change in $P_{\text{MAX}}$ in the PDMS hemisphere case despite the difference in interface conditions. On the other hand, larger $P_{\text{MAX}}$ was observed at 15 to 35 N for interface conditions with larger SCOF in case of Ecoflex hemisphere. This result implies that the SCOF can be estimated from the positive correlation between SCOF and $P_{\text{MAX}}$ if the $F_{\text{TOTAL}}$ is obvious. This is a qualitatively reasonable result with the principle of the proposed sensor. For a quantitative evaluation, it is necessary to examine how this positive correlation is calibrated.

If one-axis force sensor is stacked under the proposed sensor, for example, in a two-stage structure, the normal force component can be measured [12]. Since the positive correlation between $P_{\text{MAX}}$ and SCOF at each weight is clear in Figure 10, the estimation of SCOF by the proposed sensor is practically feasible.

In the $F_{\text{TOTAL}}$ dependency of $P_{\text{MAX}}$ and SCOF, problems remain on the calibration and classification tasks. $P_{\text{MAX}}$ of the Ecoflex hemisphere is saturated to $F_{\text{TOTAL}}$. Furthermore, as the $F_{\text{TOTAL}}$ increases, the absolute differences of the SCOF decrease opposite to those of the $P_{\text{MAX}}$. In other words, linear fitting is not possible at the time of correction. The challenging points are crucial in the interface condition classification task by SCOF. Further analysis the elastic shape is necessary.

### 3.3. Effects of $P_{\text{MAX}}$ on $\phi_{s}/\phi_{e}$ ratio

Finally, the limitation of $\phi_{s}/\phi_{e}$ ratio was investigated. Using the Ecoflex hemisphere with 12, 18, 24, 30 mm, we measured the $P_{\text{MAX}}$ with $\phi_{s}/\phi_{e}$ = 1/2, 1/3, 1/4, and 1/5, respectively ($\phi_{s}$ = 6.0 mm). Figures 11 and 12 show the relative comparison results of acrylic plate, powder, and oil. The normalized $P_{\text{MAX}}$ ratio is calculated below equation.

$$P_{\text{MAX ratio}} = \frac{|P_{\text{MAX acrylic}} - P_{\text{MAX i}}|}{(P_{\text{MAX acrylic}} + P_{\text{MAX i}})/2} \times 100 \quad (2)$$

where $i$ indicates powder or oil. For each sensor size, the results are normalized by the $P_{\text{MAX}}$ value of the acrylic plate. The horizontal axis is the input pressure ($P_{\text{IN}} = F_{\text{TOTAL}}/A; A$ is a bottom area of each hemisphere).

As the remarkable results, from 70 to 230 kPa, around 5 to 10% of the powder and around 15 to 25% of the oil difference were detected in $\phi_{s}/\phi_{e}$ = 1/3 cases. At the same time, the result of $\phi_{s}/\phi_{e}$ = 1/2 shows that the difference between powder and acrylic plate cannot be detected. In addition, as the $\phi_{s}/\phi_{e}$ ratio decreases, it shows a high change even at low pressure.

These results indicate that the proposed sensor with $\phi_{s}/\phi_{e}$ = 1/3 is the most extensive dynamic pressure range from 70 up to 230 kPa. When it comes to comparing with the $\phi_{s}/\phi_{e}$ ratio from 1/5 to 1/3, the smaller $\phi_{s}/\phi_{e}$ ratio is, the larger rate of $P_{\text{MAX}}$ is in the low input pressure. In other words, the sensitivity is improved.
This tendency is reasonable for the proposed principle. If only the pressure around \( P_{\text{MAX}} \) can be measured, it is in principle the most sensitive to changes the SCOF. The sharp decrease in sensitivity when the \( \phi_s/\phi_c \) ratio is 1/2 can be considered to be due to the dominance of pressure changes at the periphery of the contact area.

To the best of the author’s knowledge, the commercially available one-axis force sensor is available within 2.0 mm, so the proposed sensor can theoretically be designed within 10 mm.

4. Conclusion

In this paper, we propose a simple sensor structure that can estimate the SCOF using a one-axis force sensor with the elastic hemisphere. By comparing two silicone rubber with different Young’s modulus, we indicated that the softer material is important for the detection of SCOF because of the larger deformation. We experimentally compared with \( P_{\text{MAX}} \) by \( \phi_s/\phi_c \) ratio. The limitation of the \( \phi_s/\phi_c \) ratio is 1/2 and 1/3, and the best dynamic range is from 70 to 230 kPa when the \( \phi_s/\phi_c = 1/3 \) is utilized. If the proposed sensor is mounted on the shoes, the system could detect the SRFs, which means that the simple configuration of a one-axis force sensor and an elastic hemisphere makes it possible to prevent SRFs in advance.

As future works, we should measure the low SCOF region qualitatively. The measured data will be compared with the simulated data such as finite element method with nonlinear phenomena of the soft materials and contact. To demonstrate that the sensor prevents the actual SRFs, the proposed sensor will be attached to the outside of the shoes and characterized by using small module.

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No potential conflict of interest was reported by the author(s).

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