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Fundamental Research on Postural Stability in Response to Disturbance Stimuli Aimed at Preventing Falls on Winter Road Surfaces

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Abstract—**Falls on winter road surfaces in cold regions are a serious problem, especially for the elderly, as the possibility of injury is high. This study provides an important step in the developmentof a system to prevent falls by alerting people when they are walking on slippery surfaces. In this paper, as a basic study, to quantitatively investigate the effect of foot slippage on postural stability, we first created a system that presents a disturbance stimulus by moving the ground surface forward at heel strike and verified its performance. We parameterized the external disturbance stimulus by varying the acceleration and displacement of the foot.We first verified the accuracy of the system using 72 combinations of acceleration (4 to 20 m/s², in 2 m/s² increments) and acceleration distance (10 to 80 mm, in 10 mm increments) and confirmed that stimuli could be produced with high accuracy(maximum moving distance error: 80 µm, maximum acceleration percent error: 10%). Next, using the external disturbance stimulus presentation system, we investigated the combinations of foot acceleration and displacement that lead to falls in 12 healthy males. We confirmed that the conditions for external disturbance stimuli that lead to falls could be grouped within a certain range. Based on these results, we constructed a fall prediction model using a support vector machine (SVM). The overall accuracy of the model was 93%, and the fall reproduction rate was 1.00, indicating that it is possible to predict the risk of falling with high accuracy. We believe that the results of this study will provide an important foundation for the practical application of a fall prevention system on winter road surfaces.**

Index Terms—**Winter road surface, Fall prevention, External stimulus, Postural stability**

I. Introduction

In cold regions such as Hokkaido, walking outdoors in winter is a dangerous prospect. In fact, in Sapporo, after the use of studded tires was banned in 1991, the number of people who were admitted to the hospital after a fall while walking increased dramatically [1]. According to a survey by the Sapporo City Fire Department in 2023, the number of people taken to the hospital by ambulance due to snow-related falls in Sapporo City was 1887, with more than half of these being elderly people[2]. Recent trends such as the increasing number of elderly people living alone and the growth of the nuclear family have led to an increase in the number of elderly people who have to go out during the winter, and the need to prevent falls is becoming increasinglyurgent.

Falls during the winter in cold regions occur not only among the elderly but also among young people. However, falls among the elderly tend to cause more serious problems in terms of health, medical care, and welfare administration, as the resulting trauma and fractures can significantly reduce their ability to carry out daily activities. As a countermeasure against falls, research has been conducted on the use of slip-resistant shoes, focusing on improvements to the pattern and material of the soles [3–6]. Research has also been conducted from a biomechanics perspective on human movement during slips and falls [7–9]. Furthermore, the risk of falls has also been considered from a psychological perspective [10,11].

As demonstrated by the breadth of the above studies, research on slips and falls is being carried out from various perspectives, regardless of the terrain on which the falls occur. However, winter road surfaces pose a particular challenge because their state changes depending on the snowfall conditions and temperature. Given this situation, it may not be sufficient to rely on anti-slip measures such as non-slip devices for winter road surfaces. Furthermore, there have been reports that one of the factors that cause people to fall when walking is that they make incorrect judgments due to carelessness or overconfidence.On this basis, we have previously proposed a system that alerts pedestrians to the road conditions with the aim of preventing falls[12]. In this study, we developed a wearable unit that can measure foot slippage that leads to falls, with the ultimate goalof integrating it into a system that identifies locations where falls are likely to occur.System users would wear the unit while walking outdoors and then share the information in a database to alert other users approaching slippery locations. In modern times, information terminals such as smartphones and smartwatches have become widespread, and the development of communication networks has also progressed. Furthermore, the performance of various sensors and small microcomputers has also improved significantly, making it feasible to build a system like the one proposed.

Slipping can be defined as an instantaneous displacement between the ground surface and the foot, but there has been no research into what type of displacement would force a change in posture and lead to a fall. In this study, we constructed a system that presents “disturbance stimuli,” defined as stimuli that shift the ground surface forward at the location where the foot is in contact with the ground, to the foot during walking; hereafter, this system is referred to as the disturbance stimulus

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presentation system.With this system, we quantitatively clarified the factors that affect postural stability.

II. Construction of the Disturbance Stimulus Presentation System

The most common pattern of slipping during walking is when the foot slips between heel strike (the moment at which the foot makes contact with the ground) and foot flat (the moment when the entire sole of the foot makes contact with the ground), accounting for approximately 80% of cases[13]. Therefore, we focused on heel contact during a series of walking movements to investigate the effect of disturbances at this part of the gait cycle on postural stability.To simulate slipping, we presented a disturbance stimulus by moving the floor surface forward at heel strike.

To the best of our knowledge, no studies have investigated the behavior of the feet when falling on winter road surfaces. In contrast, the acceleration of the foot can reach 20 m/s^2 when a person falls on a wet bathroom floor,and there has been research on the acceleration and movement duration of the foot as a factor in slipping [14]. If the acceleration is kept constant while its duration is changed, the distance over which the foot accelerates will change. In this study, we set the acceleration and displacement of the foot as the control parameters and examined their effect on postural stability. To achieve this, it is necessary to be able to present an acceleration of up to approximately 20 m/s^2 in the external stimulus presentation system.

Initially, we planned to move the floor surface with an AC servomotor and a ball screw mechanism for linear motion. However, there were concerns that the inertial mass of the ball screw would prevent the floor surface from accelerating sufficiently. In addition, it was assumed that the vibrations and heat generated during high-speed operation would produce errors between the target position and the actual position due to structural torsion and backlash. To solve these problems and expand the range of testable accelerations, we used a linear servomotor. A linear servomotor has a flat structure with permanent magnets (stator) and electromagnets (armature) facing each other, and because it does not require a ball screw, it can operate at high speeds and accelerations. In addition, linear servomotors produce little vibration or noise, and the resolution of the attached linear scale enables positioning with an accuracy on the order of micrometers. Furthermore, one of the advantages is that a long stroke can be easily achieved by connecting the stator. However, this setup also poses the issue of requiring extremely high-precision technology in design and manufacturing.

Based on the above considerations, this study adopted a linear servomotor SGLFW2-90A380AS for the mover, SGLFM2-90714A x 2, SGLFM2-90306A for the stator, and SGD7S-200A00A000F79 for the servopack(Yaskawa Electric Co., Fukuoka, Japan). For the motor capacity, we used SigmaJunmaSize+, a servo drive selection tool made by Yaskawa Electric Co. The main specifications of the selected linear servomotor are as shown in Table 1.

In constructing the system, two linear guides were installed on either side of the linear servomotor, and a duralumin plate (500 mm × 440 mm × 9.5 mm) was attached to the top of these. A force plate (9260AA3, Kistler Japan G.K., Kanagawa, Japan) was fixed to the top of this plate to form the active motion surface (Fig. 1),the effective stroke of which is 550 mm. The system frame was made by combining aluminum frames (Misumi Group Inc., Tokyo, Japan), and linear scales (LIDA487,HeidenhainK.K., Tokyo, Japan) were attached to the sides of the frame along with linear guides. A photograph of the complete system is shown in Fig. 2.

Table 1 Main specifications of linear servomotor

Rated Speed	4.0 m/s
Maximum Speed	4.0 m/s
Rated Thrust	1120 N
Maximum Thrust	3360 N
Magnetic Attraction Force	8480 N

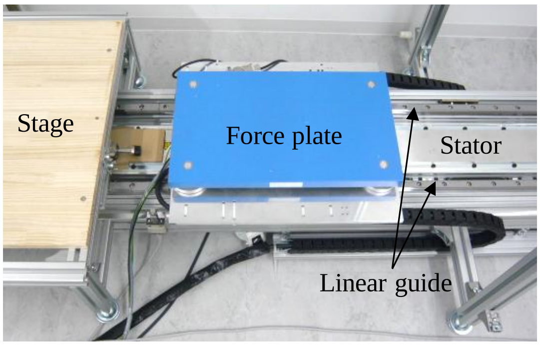

Fig. 1 Photograph of the active motion surface

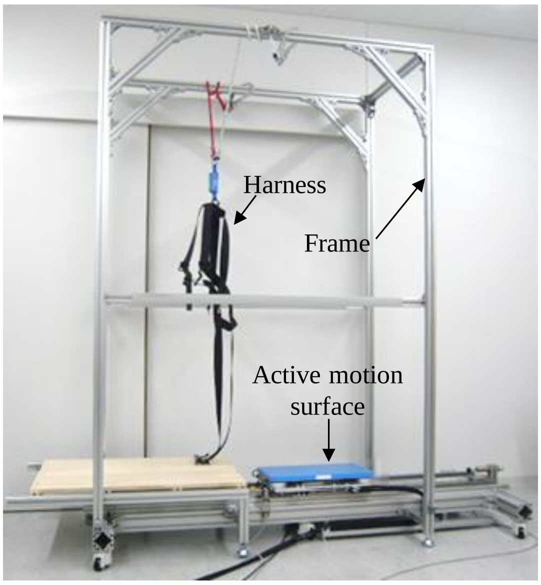

Fig. 2 Photographof the external stimulus presentation system

III. Experimental Methods

A. *Verification of basic system characteristics*

The basic characteristics of the system for presenting disturbance stimuli were verified in terms of the accuracy of the acceleration and displacement. Specifically, we tested the system by moving the initially stationary active motion surface with various target accelerations and displacements and verified whether the targets wereaccurately achieved. We evaluated a total of 72 combinations, with nine different accelerations ranging from 4 to 20 m/s^2 in increments of 2 m/s^2, and eight different displacements ranging from 10 to 80 mm in increments of 10 mm.

In the operation of a linear servomotor, there is a risk of system damage because sudden acceleration from a stopped state and immediate stopping place a large load on the system. Therefore, in this experiment, for the sake of safety,we used a deceleration operation of the same magnitude as the acceleration. For this reason, the actual distance traveled by the active motion surface is twice the target displacement.

To measure acceleration, we used a 6-axis motion sensor (MP-M6-06/2000B,MicrostoneCo., Ltd., Nagano, Japan) installed on the active motion surface. This sensor is capable of measuring 3-axis acceleration and angular velocity, and its output was collected at a sampling frequency of 1 kHz via an analog-to-digital (A/D) converter(AIO-163202F-PE,Contec Co., Ltd.,Osaka, Japan). The linear servomotor and A/D converter were controlled using Visual Basic. The distance traveled was measured using a digital caliper (CD-20AX, Mitutoyo Co., Kanagawa, Japan) to measure the displacement from the reference point to the active motion surface after movement. Three trials were performed for each combination of acceleration and displacement, and the results were averaged across trials.

B. Effect of external disturbance stimuli on human postural stability

After confirming the functionality of the external disturbance stimulus presentation system, we conducted an experiment to investigate the parameters of external disturbance stimuli that induce falls. Specifically, we reproduced the slipping of the feet on a low-friction surface by having the subject stand upright and step one foot forward onto the active motion surface, and then moving the active motion surface forward at the moment the foot touched the ground. We then quantitatively examined which combinations of acceleration and displacementwould induce a fall.

In the experiment, each subject was asked to stand on the stage of the external stimulus presentation system with both feet together and look forward (Fig. 3(a)). The subjectswere also fitted with a harness to support them when they fell and prevent injury. From an initial standing position, the subject was instructed to step forward with their dominant foot, following a cue from the measurer, and land on the active motion surface (Fig.3(b)). The step length was standardized at 600 mm.

The active motion surface was set to move forward at the moment a load of 250 N was applied. As in the verification experiment, 72 combinations of accelerations and displacements of the active motion surface, with nineacceleration values ranging from 4 to 20 m/s^2 in increments of 2 m/s^2 and eight displacements from 10 to 80 mm in increments of 10 mm, and the combinations were presented at random. After the active motion surface had moved, the subject was asked to return to their initial posture voluntarily, and we confirmed verbally whether the presented external disturbance stimulus had led to a fall.

The subjects were 12 healthy males aged 21 to 22 years, and measurements were conducted after sufficient practice to ensure that they were able to make firm contact with the active motion surface.

(a) (b)

Fig. 3 Subject posture during experiment:
(a) Initial posture,
(b)External disturbance during heel strike

IV. Experimental Results and Discussion

A. Verification of basic system characteristics

Fig. 4 (top) shows the measured acceleration for all combinations of acceleration and displacement. The horizontal axis shows the target acceleration, and the vertical axis shows the measured acceleration, with the results for each displacement of 10 to 80 mm given in different colors. There was a tendency for larger errors at high acceleration for smaller target displacements. We suspect that this is because the displacement was so small that the servomotor stopped before it had accelerated sufficiently.Fig. 4 (bottom) shows thepercent error of the acceleration for all combinations of acceleration and displacement. The horizontal axis shows the target acceleration, and the vertical axis shows the percent error of the acceleration, with the results for each displacement of 10 to 80 mm given in different colors. The results indicate no significant trend between the percent error of the acceleration and either of the stimulus parameters. The maximum percent error of the acceleration was within 10%, which is within the measurement error range (approximately 10%) of the 6-axis motion sensor itself, so we judged the experimental results to be valid.

Fig. 5 (top) shows the measured displacement for each combination of target acceleration and displacement.Fig. 5 (bottom)shows the error in the displacementfor each combination of target acceleration and displacement. The horizontal axis shows the acceleration, and the vertical axis shows the absolute value of the moving distance error, with the results each displacement of 10 to 80 mm given in different colors. There was a tendency for the absolute displacement error to increase with increasing target displacement. However, the maximum error was 80 μm

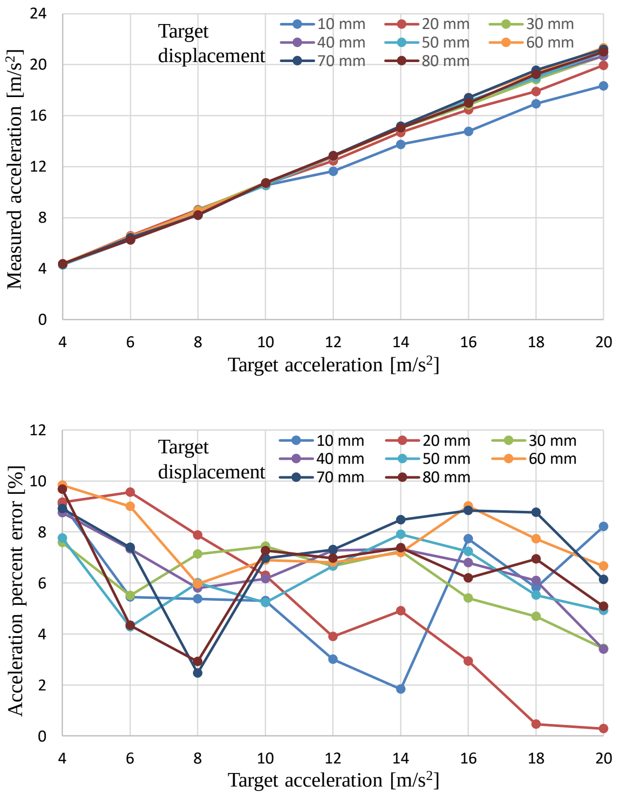

Fig. 4 Acceleration for each combination of target acceleration and displacement
(top: Measured acceleration, bottom: Percent error)

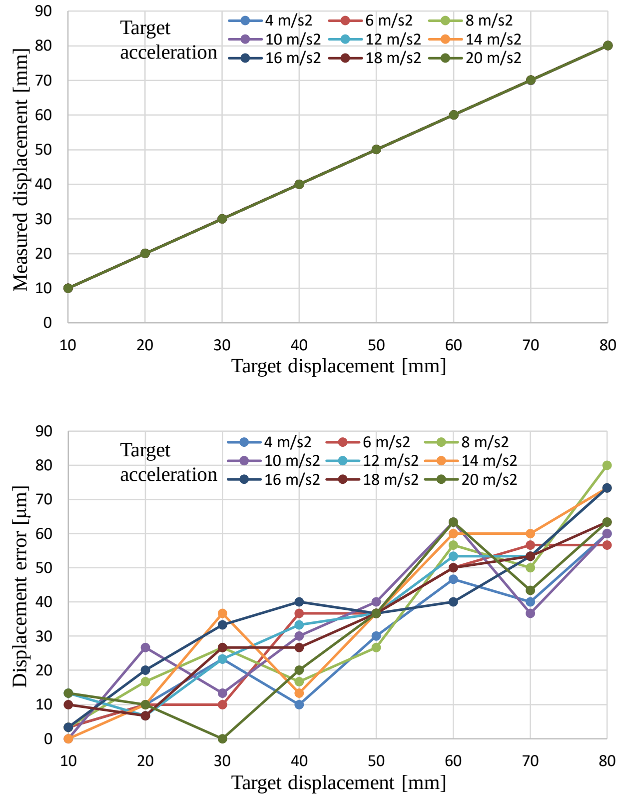

Fig. 5 Displacement for each combination of target acceleration and displacement
(top: Measured displacement, bottom: Error)

(acceleration: 8 m/s^2, acceleration distance: 80 mm), which we judged to be sufficiently small at three orders of magnitude smaller than the target distances themselves. These results demonstrate that the active motion surface in the disturbance stimulus presentation system we developed in this study has extremely high positioning accuracy. This accuracy is thought to reflect the structural characteristics and performance of the linear servomotor.

The linear servomotor is attached to a duralumin plate and a force plate, and the total mass of these components is approximately 12 kg, but it was confirmed that the active motion surface of this system can achieve the set acceleration and travel distance with high precision despite the added mass.

B. Effect of external disturbance stimuli on human postural stability

The results of a preliminary experiment to quantitatively categorize external disturbance stimuli that lead to human falls are shown in Fig. 6. The horizontal and vertical axes give the acceleration and displacement of the active motion surface,respectively, and dots are placed at the combinations of these parameters that induced a fall in two different subjects. The regions of parameter space causing a fall differed between the two subjects.However, the results reveal that a fall may occur not only when both acceleration and displacement are large but also when only one of the parameters is large.

In comparison with Subject A, Subject B fell in a more restricted area of parameter space. Therefore, we compared the temporal changes in the ground reaction force for one example of a disturbance stimulus (acceleration: 14 m/s^2, displacement: 70 mm) that caused a fall for Subject A but not Subject B. Fig. 7 shows the ground reaction force normalized by the subject's body weight plotted over time. As shown in this figure, for both subjects, the ground reaction force increased after the foot made contact with the active motion surface, reached a peak, and then decreased. This decrease indicates that the load applied to the active motion surface decreased due to the movement of the active motion surface. After that, a load approximately equal to the body weight was applied again, and a second peak occurred. This behavior was common among all subjects, but there were clear differences in the time it took to reach each peak.

Subject B applied his weight earlier than Subject A, and because he moved his weight quickly, his center of gravity moved with the active motion surface, stabilizing his posture and preventing him from falling over. In contrast, Subject A took longer to move his weight, and because only one foot moved forward, his posture became unstable and he fell. This suggests that walking speed has a significant effect on posture maintenance. The subjects in this paper were young people, but if the subjects were elderly people, who are an important target demographic for fall prevention, their walking speed would likely be slower. Furthermore, walking speed tends to be even slower on winter surfaces, which are more difficult to walk on. For the above reasons, in order to unify the conditions, in this experiment we assumed that the subjects would be walking on a winter road surface, and instructed the subjects to walk as slowly as possible.

Fig. 8 shows a graph summarizing the results of all 12

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subjects in this experiment, where each dot represents conditions under which at least two subjects fell. Conditions in which only one person fell were classified as conditions that did not result in a fall to avoid excessive warnings of falls. From these results, it was confirmed that only certain considered combinations of the acceleration and displacement of the foot lead to a fall.

C. Construction and evaluation of a fall prediction model

Based on the data obtained, we constructed a fall prediction model using a support vector machine (SVM) and verified its performance. An SVM was selected for this purpose because of the high-dimensional feature values and unbalanced data. The library used was scikit-learn (version 1.0), a machine learning library for Python, and the kernel function used was the radial basis function (RBF) kernel. The RBF kernel is suitable for fall prediction because it can handle non-linear data and is good at capturing the complex relationship between acceleration and displacement. The probability threshold was set to 0.35, lower than the usual 0.5, to improve the accuracy of the fall prediction. When training the model, 80% of the data were used for training and 20% for testing. The test data were used to verify the generalization performance of the trained model. Accuracy, precision and recall were used to evaluate performance. The overall accuracy of the model was 93%, demonstrating the utility ofan SVM model based on acceleration and displacement for fall prediction. The recall rate for the "fall" class recorded 1.00, and all 10 samples were correctly predicted. This shows that it is possible to make predictions that do not miss falls. The recall rate for the "non-fall" class was 0.80, with four out of five samples correctly predicted as non-falls, and one incorrectly predicted as a fall. This indicates that further improvement in non-fall accuracy remains a challenge.

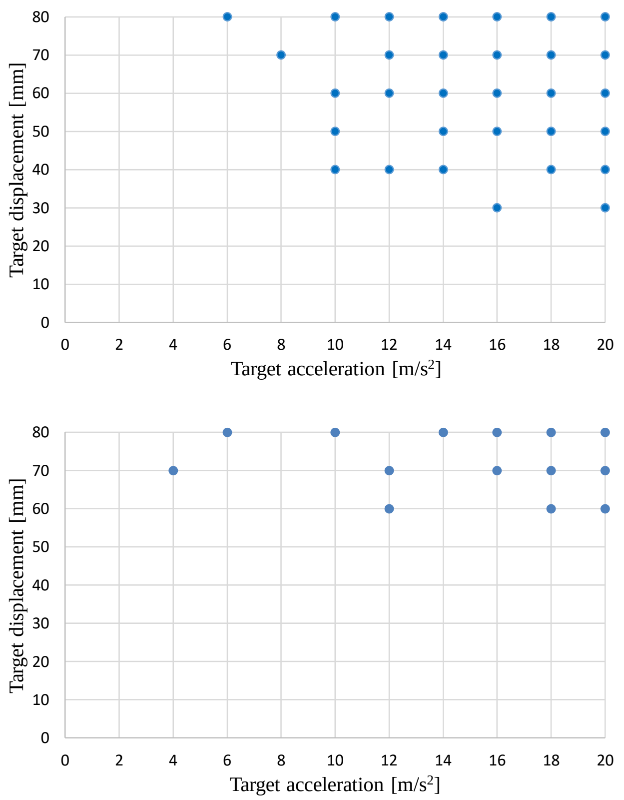

Fig. 6 Combinations of acceleration and displacement conditions leading to falls in two subjects (top: Subject A, bottom: Subject B)

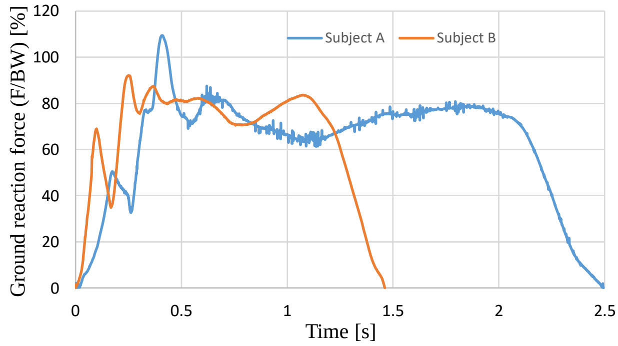

Fig. 7 Ground reaction force over time for two subjects

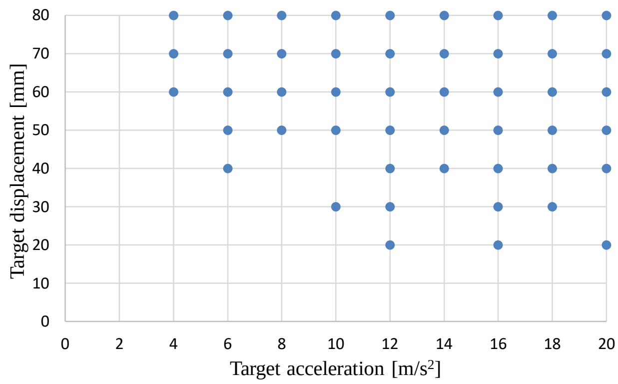

Fig. 8 Acceleration and displacement combinations that lead to a loss of stable posture

V. Conclusion

The results of this study confirmed that the acceleration and displacement of the foot induced by the disturbance stimulus presentation system we developed can be achieved with extremely high accuracy. In addition, experiments with subjects demonstrated that the combinations of acceleration and displacement of the foot leading to a fall lie within a certain range. A machine learning model using an SVM constructed based on these results was able to distinguish between falls and non-falls with high accuracy, suggesting its usefulness in fall prediction.

Future issues include the need to expand the age range of the subjects to include older people, in order to improve the fall prediction model to reflect differences in physical characteristics associated with aging. In addition, it is necessary to further improve the versatility and practicality of this system by expanding the experimental conditions to assume a variety of walking environments in daily life.

References

[1] Yoko Shintani, Fumihiro Hara and Tetsuo Akiyama, "Pedestrian Slip and Fall Accidents in the Sapporo City Center in Winter." Comprehensive Urban Studies, 85, 2005, pp.57–68.
[2] Sapporo Fire Bureau, "Self-fall on snowy roads" transport summary, Sapporo Fire Bureau, 2023.

[3] Z. Shaghayegh Bagheri, Yue Li, Atena Roshan Fekr and Tilak Dutta, “The effect of wear on slip-resistance of winter footwear with composite outsoles: A pilot study.” Applied Ergonomics 99,103611.

[4] Jennifer Hsu, Robert Shaw, Alison Novak, Yue Li, Marcus Ormerod, Rita Newton, Tilak Dutta and Geoff Fernie, “Slip resistance of winter footwear on snow and ice measured using maximum achievable incline.”Ergonomics 59, 2016, pp.717–728.

[5] Kaylie Lau, G. Fernie, and A. Roshan Fekr, “A novel method to predict slip resistance of winter footwear using aconvolutional neural network.” Footwear Science 15(3), 2023, pp.219–229.

[6] Sabrina Islam, Kunal Gide, Tilak Dutta and Z. Shaghayegh Bagheri, “The effect of tread patterns on slip resistance of footwear outsoles based on composite materials in icy conditions.” Journal of Safety Research 87, 2023, pp.453–464.

[7] Thurmon E. Lockhart, James L. Smith and Jeffrey C. Woldstad, “Effects of Aging on the Biomechanics of Slips and Falls.” Human Factors 47(4), 2005, pp.708–729.

[8] Hanatsu Nagano, W.A. Sparrow and Rezaul K. Begg, “Biomechanical characteristics of slipping during unconstrained walking, turning, gait initiation and termination.” Ergonomics 56(6), 2013, pp.1038–1048.

[9] Thurmon E. Lockhart, Jeffrey C. Woldstad and James L. Smith, “Effects of age-related gait changes on the biomechanics of slips and falls.” Ergonomics 46(12), 2003, pp.1136–1160.

[10] David John Hallford, Geoff Nicholson, Kerrie Sanders and Marita P. McCabe, “The Association Between Anxiety and Falls: A Meta-Analysis.” The Journals of Gerontology: Series B 72(5), 2017, pp.729–741.

[11] Thomas Hadjistavropoulos and Kim Delbaere, “The Psychology of Fall Risk: Fear, Anxiety, Depression, and Balance Confidence.” Cambridge University Press 4, 2021, pp.160–171.

[12] Yoko Shintani, Fumihiro Hara and Tetsuo Akiyama, “Pedestrians’ Slip and Fall Accidents in the Context of Human Error: Causes and Countermeasures.” Journal of Snow Engineering 21(2), 2005, pp.121–124.

[13] P.J. Perkins, “Measurement of slip between the shoe and ground during walking.” Walkway Surfaces: Measurement of Slip Resistance (ASTM International), 1978, pp.71–87.

[14] Hisao Nagata, Yukihiko Inoue and Hitoshi Watanabe, “A Preliminary Study on Slips, Trips and Falls in Bathing Room.” Proceedings of the Annual Meeting of Japan Ergonomics Society 44, Supplement, 2008, pp.206–207.