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Effect of heel base area and walking speed on the utilized coefficient of friction during high-heeled walking

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Abstract.
BACKGROUND: The utilized coefficient of friction (uCOF) and the risk of slipping are known to increase as the heel height of shoes increases. The heel base area of shoes can also affect the uCOF.
OBJECTIVE: The purpose of this study is to investigate the effect of the heel base area of high heels and walking speed on the uCOF during walking and their interaction effect.
METHODS: The walking experiment was conducted at the speed of 1.0 m/s and 1.25 m/s using four 9-cm high heels having different heel areas (narrow, moderate, wide, and wedge heels).
RESULTS: The peak uCOF was significantly lower when wearing the wide heels than when wearing the other heels. Wearing the narrow and moderate heels reduced the vertical ground reaction force (GRF) owing to the early timing of the peak anterior-posterior GRF and increased the peak uCOF. As the walking speed became faster, the peak uCOF became greater with more increases by the interaction effect when wearing the narrow and moderate heels than when wearing the wide and wedge heels.
CONCLUSIONS: These results imply that wearing narrow high heels should be considered carefully, as the potential for a slip could be high owing to the increase in the peak uCOF. If it is inevitable to wear narrow high heels, it is critical to walk at a slower speed than usual. It is better to wear high heels with a wide heel area, e.g., 3 cm*3 cm, rather than narrow high heels or even wedge heels to reduce the possibility of slipping.

Keywords: Slips and falls, high heels, gait biomechanics

1. Introduction

Slipping is a frequent cause of falls on the same floor and to a lower level, accounting for 55% and 23% of fall-related incidents, respectively [1]. Slipping-related falls occur across all ages in everyday life. According to reports, falls are a significant cause of nonfatal injuries for all age groups, except for the 15-to-24-year-old age group, and the second most common cause of unintentional injury-related death at home [2]. Unintentional fall-related injuries are the leading incident mostly treated in emergency departments for all age groups, except for the 10-to-24-year-old age group [3]. Slips and falls cause 21–27% of all occupational injuries in private

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industries [1, 3], and the injuries account for 48% of muscle sprains and strains and for 46% of disabling fractures [1]. Governments and organizations have worked to prevent injuries and deaths caused by slips and falls.

The utilized coefficient of friction (uCOF) and the available coefficient of friction (aCOF) have been used to predict the probability of a slip [4–7]. The uCOF is the least coefficient of friction required to maintain walking and calculated as the ratio of the resultant shear ground reaction force to the vertical ground reaction force obtained using force plates [8, 9]. On the other hand, the aCOF is the static or dynamic coefficient of friction between shoes and floor surfaces in contact and measured using tribometers [5, 6, 10]. A slip occurs when the uCOF during walking exceeds the aCOF at the shoe-floor interface, and at the instant, the foot loses traction from the floor [11]. The aCOF significantly changes depending on roughness and contaminants between shoes and floor surfaces [12, 13]; thus, the shoe materials and the flooring covered with various elements have been investigated [14], and a researcher suggested an aCOF value of 0.5 as the minimum safe slip-resistance value [15].

The uCOF is closely related to gait biomechanics, unlike the aCOF in which the interaction between shoes and floor surfaces is critical. In other words, how to walk under certain conditions is directly related to the uCOF. Age, sex, perception of slipperiness, and type of shoes were known as the conditions that affect the uCOF and the possibility of slipping [8, 16–19]. Kleiner et al. [16] reported that elderly adults walk in a manner with an increased uCOF at the toe-off phase compared with young adults and women walk in a manner with an increased uCOF at the heel contact phase compared with men. It implies that the elderly are more likely to have a backward slip of the rear foot at the toe-off phase than the young, while women are more likely to have a forward slip of the front foot at the heel contact phase than men. Lockhart et al. [17] reported that elderly and young adults have different perceptions of slipperiness even on the same surface and the inaccurate perception by the elderly causes frequent slips during walking compared with that among the young. Wearing high heels was also reported to affect the uCOF during walking significantly [19, 20]. The peak uCOF during the loading response period increased with the heel height of the shoe due to the increase in the resultant shear ground reaction force and the decrease in the vertical ground reaction force [19].

The greater uCOF during high-heeled walking can result in a higher possibility of slipping on a flooring with a low aCOF. A study reported that the rate of high-heel-related injuries has nearly doubled from 2002 to 2012, which is attributed to the increase in the use of high heels [21]. Of those injuries, 72.1% occurred in the foot and ankle, and 6.2% occurred in the fall-related body parts, such as the upper extremity and shoulder. There is an expected correlation between the use of high heels and the possibility of slipping, and the uCOF is one of the factors that can be used to predict such a possibility. However, the change in the uCOF during high-heeled walking has not been sufficiently studied. In particular, it is necessary to investigate the effect of the heel area of high heels on the uCOF, as the design of high heels varies not only in heel height but also in heel area. Luximon et al. [22] studied the effect of the heel base area of high heels on the center of pressure (CoP) during walking. The results indicated that there is a significant increase in the CoP deviation during the loading response period and a decrease in the pressure time integral over the midfoot region. These changes imply that the heel area of high heels influences the uCOF during high-heeled walking. The uCOF during walking when wearing thin high heels and wedge heels has been compared in the study of Rezgui et al. [23]; they suggested that the risk of slipping is higher for wedge heels than for thin high heels. As high heels with a wide heel area and wedge heels are different in terms of midfoot support and sole form and can have different uCOFs during walking, the change in the uCOF according to the various heel areas needs to be investigated further.

The large peak uCOF caused by the high heel height of shoes can further increase due to the narrow heel area of high heels. Therefore, the purpose of this study is to investigate the effect of the heel area on the uCOF during high-heeled walking. Since wearing high heels changes the walking speed [24, 25], and the uCOF depends on the walking speed [8, 26, 27], it is challenging to investigate the effect of the heel area on the uCOF in isolation from the walking speed at self-selected walking speed due to the combined effect. In this study, we specified the walking speed to investigate the main effects of the heel area and walking speed independently, as well as the interaction effect between the heel area and walking speed. Additionally, we investigated the correlation between the uCOF and GRF to explain the reason for the change in the uCOF according to the heel area of high heels.

2. Methods

2.1. Subjects

Since the average foot length of Korean women aged 20–29 years is reported to be 233 mm [28], 10 women with an identical shoe size of 235 mm participated in this walking experiment. No participants reported musculoskeletal disorders. Their average experiences in wearing high heels were as follows: heel height: 6.4 ± 1.65 cm, duration: 7.0 ± 4.15 hours per day, 3.2 ± 1.84 days per week, and 4.8 ± 1.14 years. The participants reported enough experience of the use of high heels; thus, they were considered to be familiar with high-heeled walking in this study. Their average age, height, and weight were 24 ± 2.72 years, 159.3 ± 3.02 cm, and 50.5 ± 4.25 kg, respectively. The Institutional Review Board of Seoul National University approved the experiment and consent document. The participants read and signed the consent document before the experiment.

2.2. Materials and equipment

We asked a maker to manufacture four high heels with the same heel height (9 cm), sole materials, and design but different heel base areas. The maker suggested four different heel areas of high heels, which are commonly used in the industry. The high heels used were narrow heels (0.9 cm*0.9 cm), moderate heels (1.5 cm*1.7 cm), wide heels (2.8 cm*2.9 cm), and wedge heels (one-piece of the sole and the heel). Figure 1 shows the manufactured high heels. The walking experiment using these high heels was conducted on a treadmill with two force plates inserted (Bertec, OH, USA). The flooring of the treadmill consisted of two separate rubber belts for each of the left and right sides. Twenty-one reflective markers were attached on the body and shoes: however, only toe and heel markers were used to calculate the stride length in this study. Motion capture was performed to collect the walking data using six motion capture cameras (Motion Analysis, CA, USA).

Fig. 1. Four manufactured high heels with different heel areas; from left to right, narrow heels (0.9 cm*0.9 cm), moderate heels (1.5 cm*1.7 cm), wide heels (2.8 cm*2.9 cm), and wedge heels (one-piece of the sole and heel).

2.3. Experimental procedure

The walking speeds were specified in this study to exclude the variation of the uCOF caused by the difference in the self-selected walking speed. As a study reported that 1.27 m/s is the average walking pace for women [29], we selected 1.25 m/s as the normal walking speed. Further, 1.0 m/s, which is 20% slower than the normal walking speed, was selected as the slow walking speed. We also attempted to collect walking data at a fast speed of 1.5 m/s; however, the subjects had difficulty walking wearing the high heels at the pace without losing stability. Therefore, we excluded the high-heeled walking experiment at the fast speed, unlike the original plan. The walking trials were conducted in a randomized order using the four high heels at the given walking speeds. The participants were asked to walk on the treadmill for 30 seconds, and data of the force plates and markers were recorded at 800 Hz and 200 Hz, respectively. There was a 3-minute break time after each walking trial.

2.4. Data processing

A 55th-order low-pass Butterworth filter was used to filter the data of the force plates and markers at cutoff frequencies of 30 Hz and 10 Hz, respectively. The vertical ground reaction force was used to determine the gait event, such as heel contact and toe-off. Five gait cycles for each left leg and right leg were extracted. The anterior-posterior GRF (GRF_{AP}), medial-lateral GRF (GRF_{ML}), and vertical GRF (GRF_{V}) were normalized according to the body mass of each participant and averaged together for the five cycles. The utilized coefficient of friction (uCOF) was calculated as the ratio of the resultant shear GRF to the vertical GRF as follows [26].

$$\text{uCOF} = \frac{\text{Resultant shear GRF}}{\text{Verticla GRF}} = \frac{\sqrt{GRF_{AP}{}^2 + GRF_{ML}{}^2}}{GRF_V} \tag{1}$$

In this study, we only focused on investigating the first peak uCOF, which is the maximum uCOF during the loading response period, as most slips are expected to occur during this period [13]. The stride lengths were calculated on the basis of the midpoint between the toe and heel markers at heel contact. The stance and swing ratios were defined as the percentages of stance and swing time per stride time during a cycle of walking, respectively. MATLAB (MathWorks, MA, USA) was used for the data calculation. Two-way repeated-measures analysis of variance with LSD *post-hoc* test was performed to investigate the main effects of the heel area and walking speed, as well as the interaction effect between them. A correlation analysis was conducted to investigate the relationship between the change in the uCOF and GRF. The significance level was set at 0.05, and the statistical analysis was performed using SPSS (IBM, NY, USA).

3. Results

3.1. *Main effect of the heel area during high-heeled walking and correlation between the uCOF and GRF*

Table 1 shows the main effect of the heel area on the uCOF during high-heeled walking at the given speeds of 1.0 m/s and 1.25 m/s. The magnitude of the peak uCOF decreased as the heel area increased from the narrow heels to the wide heels; however, it increased again when wearing the wedge heels (Table 1(A)). The *post-hoc* test revealed that the peak uCOF when wearing the wide heels is significantly different from those when wearing the other heels. The timing of the peak uCOF occurred at the earlier loading response period when wearing the narrow heels and the moderate heels than when wearing the wide heels and the wedge heels; however, there was no significant difference in the timing between the wide heels and the wedge heels (Table 1(A)). The correlation analysis showed that there is a significant negative correlation between the magnitude of the peak uCOF and the timing of the peak uCOF ($r = -0.591$, $p < 0.001$).

The change in the peak uCOF was related to the timing of the peak GRF_{AP} (Table 1(B)). Neither the magnitude nor the timing of the peak GRFs was significantly different according to the heel area, except for the timing of the peak GRF_{AP}. The time to the peak GRF_{AP} was shorter when wearing the narrow heels and the moderate heels than when wearing the wide heels and the wedge heels (Table 1(B)), similar to the change in the timing of the peak uCOF (Table 1(A)). The timing of the peak GRF_{AP} had a

Table 1
uCOF, GRF, and stride parameters according to the heel area during high-heeled walking

	Heel area (cm*cm)				*p*-value
	Narrow 0.9*0.9	Moderate 1.5*1.7	Wide 2.8*2.9	Wedge One-piece	
(A) uCOF during loading response					
Peak uCOF (unitless)	0.215^{a}	0.212^{a}	0.203^{b}	0.211^{a}	0.005*
t of the peak uCOF (%)	$15.43^{a,b}$	$15.94^{a,b}$	18.38	18.11	<0.001*
(B) GRF during loading response					
Peak GRF_{AP} (N/Kg)	2.153	2.144	2.137	2.193	0.425
t of the peak GRF_{AP} (%)	17.88^{a}	$18.16^{a,b}$	19.16	19.08	0.023*
Peak GRF_{ML} (N/Kg)	1.025	1.004	1.026	1.032	0.624
t of the peak GRF_{ML} (%)	29.76	29.83	30.59	30.82	0.321
Peak GRF_{V} (N/Kg)	11.971	11.887	12.130	11.987	0.098
t of the peak GRF_{V} (%)	24.69	25.10	25.05	25.78	0.352
(C) GRF at the peak uCOF					
GRF_{AP} (N/Kg)	2.045^{b}	2.046^{b}	2.071	2.148	0.034*
GRF_{ML} (N/Kg)	$0.371^{a,b}$	$0.382^{a,b}$	0.528	0.534	0.004*
GRF_{V} (N/Kg)	$9.765^{a,b}$	$9.926^{a,b}$	10.805	10.702	<0.001*
(D) Stride parameters					
Stride length (m)	1.080	1.090	1.087	1.093	0.310
Stride time (s)	0.964	0.971	0.970	0.974	0.281
Stance ratio (%)	63.50^{b}	$63.63^{a,b}$	64.16	64.23	0.009*
Swing ratio (%)	36.50^{b}	$36.37^{a,b}$	35.84	35.77	0.009*

*Significant difference via two-way repeated-measures analysis of variance. [a,b]Significant difference in comparison with the wide heels and the wedge heels. *t*: timing of the uCOF or the GRF as a percentage of the stance phase. Stance or swing ratio: percentage of the stance or swing time per stride time. uCOF: utilized coefficient of friction; GRF: ground reaction force; GRF_{AP}: anterior-posterior ground reaction force; GRF_{ML}: medial-lateral ground reaction force; GRF_{V}: vertical ground reaction force.

strong positive correlation to the timing of the peak uCOF ($r = 0.701$, $p < 0.001$) and a negative correlation to the magnitude of the peak uCOF ($r = –0.523$, $p < 0.001$).

The increased peak uCOFs when wearing the narrow heels and the moderate heels were mainly attributed to the significantly reduced GRF_V at the peak uCOF compared with that when wearing the wide heels and the wedge heels (Table 1(C)). Even though the GRF_{ML} and the GRF_{AP} when wearing the narrow heels and the moderate heels decreased slightly with statistical significances, the changes were negligible in comparison with the difference in the GRF_V.

At the given walking speeds, the stride length and time were not significantly different according to the heel area during high-heeled walking; however, the stance and swing ratios were significantly different (Table 1(D)). The stance ratio decreased, whereas the swing ratio increased when wearing the narrow heels and the moderate heels.

3.2. *Main effect of the walking speed during high-heeled walking and interaction effect between the heel area and walking speed*

The left side of Table 2 shows the main effect of the walking speed. The magnitude of the peak uCOF was smaller at the slow speed than at the normal speed, and the timing of the peak was earlier (Table 2(A), left side). The change in the peak uCOF according to the walking speed was related to the magnitude of the peak GRF_{AP}, GRF_{ML}, and GRF_V, unlike the effect of the heel area, which correlated with the timing of the peak GRF_{AP}. The peak GRF_{AP}, GRF_{ML}, and GRF_V decreased significantly during walking at the slow speed compared with those at the normal speed; however, there were no significant changes in the timings of the peaks (Table 2(B), left side). Similarly, the magnitudes of the GRF_{AP} and GRF_V at the peak uCOF decreased during walking at the slow speed (Table 2(C), left side). The stance and swing ratios did not change according to the walking speed. The stride length and time were shorter and longer during walking at the slow speed than at the normal speed, respectively (Table 2(D), left side).

The right side of Table 2 and Fig. 2 show the interaction effect between the heel area and walking speed. Only in the magnitude of the peak uCOF, there was a significant interaction between the heel area and walking speed (Table 2(A), right side). The difference in the peak uCOF between the slow speed and the normal speed was larger when wearing the narrow heels and the moderate heels than when wearing the wide heels and the wedge heels. The value differences were 0.0205 and 0.0211 when wearing the narrow heels and the moderate heels, respectively, and 0.0134 and 0.0114 when wearing the wide heels and the wedge heels, respectively. Figure 2 shows that the peak uCOF increases with higher gains during walking when wearing the narrow heels and the moderate heels than when wearing the wide heels and the wedge heels, as the walking speed increases.

4. Discussion

The purpose of this study was to investigate the change in the uCOF during walking according to the heel area of high heels and walking speed and their interaction effect.

The peak uCOF is known to increase during walking as the heel height of high heels increases [19, 20]. This study showed that not only the heel height of high heels but also the heel area affects the peak uCOF. As the heel area became smaller from the wide heels (2.8 cm*2.9 cm) to the narrow heels (0.9 cm*0.9 cm), the peak uCOF during high-heeled walking increased significantly (Table 1(A)). However, wearing the wedge heels did not yield a lower peak uCOF compared with wearing the wide heels, although the wedge heels had a larger one-piece heel base area. Rather, the peak uCOF of the wedge heels increased with statistical significances compared with that of the wide heels (Table 1(A), LSD *post-hoc* test: $p = 0.046$). Our previous study also showed a slight increase in the peak uCOF when wearing the wedge heels compared with that when wearing the wide heels; however, there was no significant difference between them [9]. With the added walking data at the slow speed in this study, the increasing trend of the peak uCOF when wearing the wedge heels was evident. Rezgui et al. [23] also reported that the peak uCOF is greater when wearing wedge heels with a 12.5-cm heel height than when wearing thin heels with a 12.2-cm heel height. Our study showed that the wedge heels have an increased peak uCOF compared with the wide heels; however, there was no significant difference between the wedge heels and the narrow heels. Since Rezgui et al. did not describe the heel area of the thin heels and shoe design of the experimental shoes used in detail, it is difficult to compare between the results of our study and Rezgui et al.'s study directly. Nevertheless, we agree

Table 2
uCOF, GRF, and stride parameters according to the walking speed during high-heeled walking (left side) and the interaction effect between the heel area and walking speed (right side)

	Speed (m/s)			Interaction
	Slow	Normal		Heel Area*Speed
	1.0	1.25	*p*-value	*p*-value
(A) uCOF during loading response				
Peak uCOF (unitless)	0.202	0.218	0.022*	0.036*
t of the peak uCOF (%)	16.61	17.32	0.044*	0.953
(B) GRF during loading response				
Peak GRF_{AP} (N/Kg)	1.924	2.389	<0.001*	0.227
t of the peak GRF_{AP} (%)	19.01	18.12	0.105	0.343
Peak GRF_{ML} (N/Kg)	0.957	1.086	0.016*	0.215
t of the peak GRF_{ML} (%)	30.81	29.70	0.278	0.327
Peak GRF_{V} (N/Kg)	11.558	12.429	<0.001*	0.998
t of the peak GRF_{V} (%)	26.18	24.13	0.121	0.642
(C) GRF at the peak uCOF				
GRF_{AP} (N/Kg)	1.835	2.321	<0.001*	0.617
GRF_{ML} (N/Kg)	0.428	0.480	0.283	0.393
GRF_{V} (N/Kg)	9.549	11.050	<0.001*	0.590
(D) Stride parameters				
Stride length (m)	1.018	1.157	<0.001*	0.604
Stride time (s)	1.015	0.925	<0.001*	0.732
Stance ratio (%)	64.21	63.54	0.077	0.050
Swing ratio (%)	35.79	36.46	0.077	0.050

*Significant difference via two-way repeated-measures analysis of variance. *t*: timing of the uCOF or the GRF as a percentage of the stance phase. Stance or swing ratio: percentage of the stance or swing time per stride time. uCOF: utilized coefficient of friction; GRF: ground reaction force; GRF_{AP}: anterior-posterior ground reaction force; GRF_{ML}: medial-lateral ground reaction force; GRF_{V}: vertical ground reaction force.

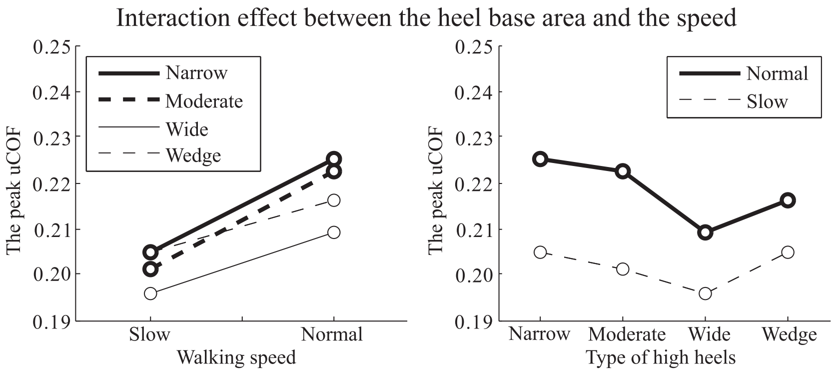

Fig. 2. Interaction effect between the heel area (narrow heels, moderate heels, wide heels, and wedge heels) and walking speed (slow speed: 1.0 m/s and normal speed: 1.25 m/s). It shows a larger increase in the peak uCOF as the walking speed increases during walking when wearing the narrow heels and the moderate heels than when wearing the wide heels and the wedge heels. uCOF: utilized coefficient of friction.

with their opinion that wearing wedge heels is not better than wearing thin high heels in terms of slipping during walking. Our finding additionally shows that wearing high heels with a heel area of approximately 3 cm*3 cm can reduce the possibility of slipping with a lower uCOF compared with wearing narrower high heels or even wedge heels.

The increase in the peak uCOF due to the narrow heel area of the high heels correlated to the change in the timing of the peak GRF_{AP} during the loading response period (Table 1(B); correlation analysis between the timing of the peak uCOF and the timing of the GRF_{AP}: $r = 0.701$, $p < 0.001$). This timing change implies that the foot rolls rapidly from the rear to the fore to move the CoP to a stable location. Figure 3 shows the CoP movement according to the different heel areas of the high heels. The graph indicates that the CoP moves to the midfoot faster when wearing the narrow heels and the moderate heels during the loading response period (Fig. 3). This

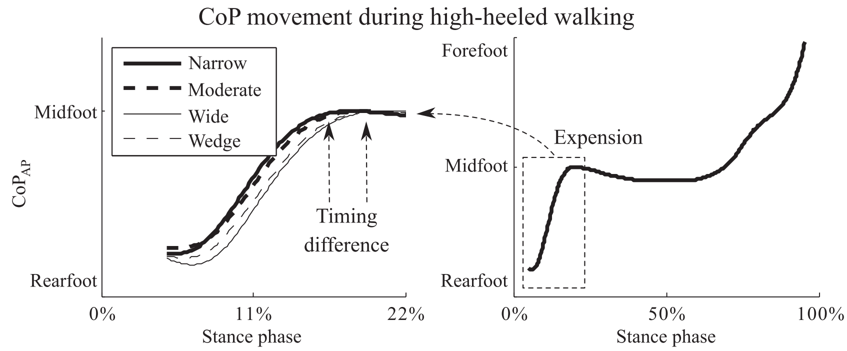

Fig. 3. Anterior-posterior center of pressure (CoP_{AP}) movement during high-heeled walking at the different heel areas. It shows faster CoP_{AP} movements to the midfoot during walking wearing the narrow heels and the moderate heels than when wearing the wide heels and the wedge heels. The CoP_{AP} was calculated using the ground reaction forces and moments and adjusted through the toe and heel markers.

timing change resulted in the reduced GRF_V owing to the early timing of the peak GRF_{AP} and eventually the increased peak uCOF during high-heeled walking with the smaller heel base area (Table 1). This tendency was revealed during high-heeled walking with the narrow heels (0.9 cm*0.9 cm) and the moderate heels (1.5 cm*1.7 cm) in this study. Further studies are needed to understand the increased peak uCOF when wearing the wedge heels. One possible explanation is that the wedge heels are weighty, thereby, influencing the GRF_{AP} and the uCOF.

While the heel area of the high heels was related to the change in the timing of the foot movement, the walking speed affected the magnitude of the GRFs from the feet (Table 2(B), left side). The increases in the peak uCOF caused by reducing the heel area and increasing the walking speed are attributed to two separate reasons: change in the timing of the GRF and change in the magnitude of the GRF. However, these two factors are not independent, and the increasing effect is amplified when the factors are combined (Table 2(A), right side and Fig. 2). If individuals tend to slow down during walking when wearing narrow high heels, it would be attributed to lowering the peak uCOF and reducing the potential for a slip. Since the small increase in the walking speed leads to the more significant increases in the peak uCOF when wearing the narrow heels than when wearing the wide heels due to the interaction effect (Table 2(A), right side and Fig. 2), walking slowly is imperative when wearing narrow high heels.

Several studies predicting the probability of a slip have shown that the potential for a slip can increase considerably during walking even with a slight change in the uCOF [4–6]. In this study, the value difference in the peak uCOF between the narrow heels and the wide heels was approximately 0.01 (Table 1(A)). According to Beschorner et al. [4], an increase of 0.01 in the uCOF brings a 73% higher odds of slipping during walking. Even if the change in the peak uCOF seems to be small, it should be noted that the difference can cause severe slips and falls, especially at floor conditions having a low aCOF.

In this study, we utilized the treadmill for the experiment to control the walking speed accurately. Several studies have shown that the gait patterns on the ground and treadmill are so similar that using a treadmill is suitable for movement analysis [30–33]. A study suggested that treadmill walking during the mid- and late stance periods may differ from ground walking in terms of the GRF_V [34]; however, this study focused on the change in the uCOF and GRF during the loading response period, which is in the early stance period. Therefore, we considered that the walking experiment on the treadmill is appropriate.

There are several limitations in this study, which need to to be mentioned. For the walking experiment, the subjects' walking speeds were assigned (1.0 m/s and 1.25 m/s) rather than using a self-selected walking speed to investigate not only the main effect of the heel area and walking speed but also their interaction effect. If the walking experiment is conducted at a self-selected walking speed, the subjects could slowly walk when wearing the narrow heels and the moderate heels compared with the wide heels and the wedge heels. Thus, there could be no difference in the peak uCOF, as the increased peak uCOF during walking when wearing the narrower heels would decrease due to the slow speed. There is a study that individuals adjust their gait patterns significantly when there is an expected factor increasing the risk of slipping even if they are asked to walk naturally [35]. The self-selected walking speed can be altered when wearing the narrower heels, as the small heel area would be one of the expected factors increasing the risk of slipping. The effect of the heel base area on the uCOF may differ if walking at a self-selected speed is allowed.

Another limitation is that only three heel areas (narrow: 0.9 cm*0.9 cm, moderate: 1.5 cm*1.7 cm, and wide: 2.8 cm*2.9 cm) were utilized in this study, except for the wedge heels (one-piece of the sole and the heel). Since the manufacturer recommended these heel base areas as popular shoe designs, we selected the three heel areas for the walking experiment. The results showed the lowest uCOF during walking on the high heels with a wide heel area; however, it cannot be asserted that this is the optimum heel area of high heels to reduce the possibility of slipping. The peak uCOF could be lower if the walking experiment is conducted using wider heel areas such as 4 cm*4 cm and 5 cm* 5 cm, as high heels with a heel width similar to the foot's heel width (approximately 5 cm) are known to have less influence on gait patterns [36]. Our finding only shows that heels with a heel area of 3 cm*3 cm are helpful compared with narrower heels or wedge heels in reducing the peak uCOF and the risk of slipping.

5. Conclusion

Wearing high heels having a smaller heel area was found to increase the peak uCOF due to the early timing of the peak GRF_{AP} during the loading response period. Further, the heel area interacted with the walking speed; the peak uCOF increased more when wearing the narrow high heels than when wearing the wide high heels as the walking speed became faster. The peak uCOF when wearing the wide heels was significantly smaller than that when wearing the wedge heels, although the wedge heels had a larger heel base area than the wide heels. Wearing narrow high heels should be considered carefully due to the increased peak uCOF and the high possibility of slipping. If it is inevitable to wear narrow high heels, it is recommended to walk at a slower speed than usual. It is also suggested to wear high heels with a wide heel base area, e.g., 3 cm* 3 cm, rather than narrow high heels or wedge heels to reduce the potential for a slip.

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Conflict of interest

None to report.

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