Effect of Heel Area on Utilized Coefficient of Friction During High-Heeled Walking

Sumin Park and Jaeheung Park(✉)

Department of Transdisciplinary Studies, Graduate School of Convergence Science and Technology, Seoul National University, Suwon 16229, Republic of Korea
park73@snu.ac.kr

Abstract. The purpose of this study is to investigate the effect of heel area on the utilized coefficient of friction (uCOF) during high-heeled walking and to explain the change of the uCOF by understanding the gait patterns. Four high heels with different heel areas (Narrow: 0.9 * 0.9 cm, Moderate: 1.5 * 1.7 cm, Wide: 2.8 * 2.9 cm, Wedges: one piece of the sole and heel) were manufactured for walking experiments. Ten females walked at 1.25 m/s on a treadmill with two force plates inserted, and the walking data were collected by motion capture system. The uCOF during stance phase was calculated from ground reaction forces (GRFs). The peak uCOF and the peak GRFs during loading response period was identified according to the heel area. One-way repeated measure analysis of variance and correlation analysis were performed for the peak uCOF and the peak GRFs. As the heel area became narrower, the peak uCOF increased significantly. However, there was no significant difference in the peak uCOF between the wide heels and wedge heels. The changed peak uCOF according to the heel area correlated with the change in timing of the peak uCOF. The peak uCOF and the peak anterior-posterior GRF occurred in early loading response period when wearing the narrow heels than the wide heels, although the magnitudes of the peak GRFs were consistent. The potential for slipping during high-heeled walking can be increased at narrow heel area since the horizontal shear force reaches the peak quickly before the vertical force is sufficiently large with weight acceptance.

Keywords: Utilized coefficient of friction · High-heeled walking
Heel area

1 Introduction

Slips occur during walking when the adhesive friction between the foot and the floor is lost. Unexpected slips cause muscle sprains and strains, and even more severe musculoskeletal injuries if slips lead to falls [1]. 40–50% of slips contribute to falls [2], and slips and falls account for about 20% of all occupational accidents [1].

In industry, it is important to understand slip-resistance of the shoes and the workplace floor in order to reduce the occupational accidents caused by slips and falls. The slip-resistance is calculated as the available coefficient of friction (aCOF), which is either the static or dynamic coefficient of friction (COF) between the outsole of the shoe

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and the floor surface. Researchers investigated the aCOF in workplace floors covered with various materials, because the slip-resistance changes when the floor is contaminated. A study reported that slips did not happen during walking across a clay-covered beam with static COF of 0.41 in shoes with urethane sole, but did occur during walking across an oil-covered beam with static COF of 0.20 [3]. Perkins and Wilson [4] mentioned that dynamic COF varies depending on how the shoe moves on the surface under different contaminant conditions and slips can occur in a wet vinyl tile floor with dynamic COF of 0.30 if the heel strikes the floor at a landing speed of more than 2 cm/s. Miller [5] suggested aCOF of 0.50 as a minimum safety standard of the shoe-floor interface for the workplace surface.

To predict the potential for slipping, the utilized coefficient of friction (uCOF) was also investigated as well as the aCOF [6–8]. The aCOF is usually measured by tribometers to illustrate the slip-resistance of the shoes and the floor [6], while the uCOF means the friction required to continue the movement and is calculated by force plates as the ratio of the resultant shear ground reaction force to the vertical ground reaction force during walking [9]. The uCOF is affected by gait biomechanics, and thus it depends on age, sex, walking speed, etc. [9–11]. If the peak uCOF exceeds aCOF of the shoe-floor interface, the foot slides due to the loss of traction with the floor [12]. It is reported that wearing high heels increases the peak uCOF during walking and the risk of slipping is higher during high-heeled walking than normal walking due to the increased peak uCOF [12].

The high risk of slipping during high heeled walking can increase more depending on the heel area of high heels even with the identical heel height due to changed uCOF. It is hypothesized that the peak uCOF increases as the heel area becomes narrower, although the heel height is identical. Therefore, the purpose of this study is to investigate the effect of heel area on uCOF during high-heeled walking with the identical heel height and to explain the change of uCOF by understanding the gait patterns according to the heel area.

2 Materials and Methods

2.1 Subjects

Ten females with a shoe size of 235 mm, who are experienced in wearing high heels, participated in walking experiments. Their average height, weight, and age are 159.3 ± 3.02 cm, 50.5 ± 4.25 kg, and 24 ± 2.72 years, respectively. The participants read and signed a written informed consent document, which is approved by the Institutional Review Board of Seoul National University, before the experiments. All participants reported no musculoskeletal disorders.

2.2 Instrumentation

Four shoes with different heel areas having the identical heel height of 9 cm were made of the identical material from a manufacturer. Figure 1 shows the manufactured shoes (Narrow heels: 0.9 * 0.9 cm, Moderate heels: 1.5 * 1.7 cm, Wide heels: 2.8 * 2.9 cm, Wedge heels: one piece of the sole and the heel). Two force plates (AMTI, MA, USA), which are inserted in a treadmill, were used to obtain ground reaction forces (GRFs) during walking. The treadmill's floor is made of two separate rubber belts for each of the right foot and left foot. The reflective markers attached to the toe and heel of the shoes were used to calculate stride length and stride time. Six cameras (Motion Analysis, CA, USA) were used to capture the markers by motion capture system.

Fig. 1. The manufactured shoes (Narrow heels: 0.9 * 0.9 cm, Moderate heels: 1.5 * 1.7 cm, Wide heels: 2.8 * 2.9 cm, Wedge heels: one piece of the sole and the heel)

2.3 Experimental Procedures

It was checked whether the shoes of 235 mm are fit with the subjects' feet or not. In case there is a small gap between the shoes and feet of the subjects, thin soles were inserted inside of the shoes. The participants walked on the treadmill at a speed of 1.25 m/s for 30 s. Force data and marker data were recorded at 800 Hz and 200 Hz, respectively. Since comfortable walking speed for women was reported as approximately 1.272 m/s [13], the speed of 1.25 m/s was chosen for the experiments. Walking trials according to the shoe condition were performed in a randomized order with a 3 min break time after each trial.

2.4 Data Process

The force data and marker data were filtered by a 5th-order low-pass Butterworth filter with a cutoff frequency of 30 Hz and 10 Hz, respectively. Anterior-Posterior GRF (GRF_{AP}), Medial-Lateral GRF (GRF_{ML}), and Vertical GRF (GRF_V) of five cycles were extracted for each of the left foot and right foot. The timing of heel-strike and toe-off were determined by GRF_V to distinguish stance phase, swing phase, and a cycle of walking. The averaged GRF_{AP}, GRF_{ML}, and GRF_V of each subject according to the heel area were calculated and normalized by the body mass of each subject. The utilized coefficient of frictions (uCOF) of each subject during stance phase was calculated as the ratio of the averaged resultant shear GRF (GRF_R) to the averaged GRF_V.

$$\mathrm{uCOF} = \frac{\text{Resultant shear GRF}}{\text{Vertical GRF}} = \frac{\sqrt{GRF_{AP}^2 + GRF_{ML}^2}}{GRF_V}$$

The peak uCOF was defined as the maximum uCOF during weight acceptance since most of the slips occur in the forward direction during the period [4]. Stride lengths of five cycles for each of the left foot and right foot were determined based on the midpoint between the toe and heel markers at the heel strike. The averaged stride length, stride time, stance ratio, and swing ratio were calculated according to the heel area. The stance ratio and swing ratio indicate the percentages of stance time and swing time per stride time respectively during a cycle of walking. Statistical analysis was performed using one-way repeated measure analysis of variance (RM-ANOVA) with the Huynh-Feldt correction and the LSD post-hoc test. Correlation analysis was also performed to understand the relationship between the changes in uCOF and GRFs. The significance level was set to less than 0.05. Data process and statistical analysis were conducted by MATLAB (MathWorks, MA, USA) and SPSS (IBM, NY, USA) software respectively.

3 Results

The magnitude of the peak uCOF increased significantly as the heel area of the high heels became narrower (Table 1(A)).

The peak uCOF when wearing the narrow heels and the moderate heels were 1.08 times (post-hoc test, $p = 0.003$) and 1.06 times (post-hoc test, $p = 0.011$) higher respectively than the peak uCOF when wearing the wide heels (Table 1(A)). There was no significant difference in the peak uCOF between the wedge heels and the wide heels (post-hoc test, $p = 0.138$).

The changed magnitude of the peak uCOF according to the heel area correlated with the change in timing of the peak uCOF (correlation analysis, $r = -0.674$, $p < 0.001$). The peak uCOF occurred in the early loading response period when wearing the narrow heels (post-hoc test, $p = 0.003$) and the moderate heels (post-hoc test, $p = 0.001$) than the wide heels (Table 1(A)). There was also a relationship between the timing of the peak uCOF and the timing of the peak GRF_{AP} (correlation analysis, $r = 0.889$, $p < 0.001$). Like the peak uCOF, the peak GRF_{AP} occurred in the early loading response period when wearing the narrow heels than the wide heels, while the timing of the peak GRF_{ML} and the peak GRF_V did not differ significantly (Table 1(B)). The magnitudes of the peak GRF_{AP}, the peak GRF_{ML}, and the peak GRF_V were consistent regardless of the heel area (Table 1(B)).

According to the results of the magnitudes of the GRFs at the peak uCOF (Table 1 (C)), both the GRF_{ML} and GRF_V were smaller when wearing the narrow heels than the wide heels due to the changed timing of the peak uCOF. Meanwhile, the GRF_{AP} and GRF_R at the peak uCOF were not statistically significant depending on the heel area.

The stride length and stride time did not show any difference according to the heel area during walking at 1.25 m/s. However, the stance ratio and swing ratio when wearing the narrow heels decreased and increased respectively than the wide heels and the wedge heels (Table 2). The changed stance or swing ratio also correlated with the change in the timing of the peak GRF_{AP} (correlation analysis, $r = 0.650$, $p < 0.001$).

Table 1. Change of uCOF and GRFs according to heel area during high-heeled walking

	Heel area				*p*-value
	Narrow (0.9 * 0.9 cm)	Moderate (1.5 * 1.7 cm)	Wide (2.8 * 2.9 cm)	Wedge (One piece)	
(A) uCOF in loading response					
Peak uCOF (unitless)	0.225[a]	0.222[a]	0.209	0.216	0.003*
Timing of the peak uCOF (%)	15.8[a,b]	16.2[a,b]	18.7	18.5	<0.001*
(B) GRFs in loading response					
Peak GRF_{AP} (N/Kg)	2.406	2.391	2.340	2.421	0.405
Timing of the peak GRF_{AP} (%)	17.2[a]	17.7[a,b]	19.0	18.7	0.022*
Peak GRF_{ML} (N/Kg)	1.090	1.049	1.095	1.112	0.191
Timing of the peak GRF_{ML} (%)	29.6	28.9	30.4	29.9	0.123
Peak GRF_V (N/Kg)	12.405	12.316	12.570	12.426	0.165
Timing of the peak GRF_V (%)	23.4	24.3	23.9	24.9	0.508
(C) GRFs at the peak uCOF					
GRF_{AP} (N/Kg)	2.308	2.292	2.297	2.385	0.286
GRF_{ML} (N/Kg)	0.411[b]	0.395[a,b]	0.537	0.578	0.007*
GRF_V (N/Kg)	10.543[a,b]	10.603[a,b]	11.544	11.512	<0.001*
GRF_R (N/Kg)	2.357	2.339	2.382	2.476	0.080

NOTE: *means there is a significant difference by RM-ANOVA. [a]indicates a significant difference in comparison with the wide heels by post-hoc test. [b]indicates a significant difference in comparison with the wedge heels by post-hoc test. The timing of the uCOF or GRFs is presented as a percentage of stance phase.

4 Discussion

It has been reported that the peak uCOF during high-heeled walking increases due to the increased GRF_R and decreased GRF_V as the heel height of the shoe increases, and it leads to the high risk of slipping [12]. The results of this study show that the potential

Table 2. Change of gait parameters according to heel area during high-heeled walking

	Heel area				*p*-value
	Narrow (0.9 * 0.9 cm)	Moderate (1.5 * 1.7 cm)	Wide (2.8 * 2.9 cm)	Wedge (One piece)	
Stride length (m)	1.15	1.16	1.16	1.16	0.122
Stride time (s)	0.92	0.93	0.92	0.93	0.100
Stance ratio (%)	62.98[a,b]	63.39[a,b]	63.92	63.88	0.011*
Swing ratio (%)	37.02[a,b]	36.61[a,b]	36.08	36.12	0.011*

NOTE: *means there is a significant difference by RM-ANOVA. [a]indicates a significant difference in comparison with wide heels by post-hoc test. [b]indicates a significant difference in comparison with wedge heels by post-hoc test. The stance ratio and swing ratio indicate the percentages of stance time and swing time per stride time respectively.

for slipping during high-heeled walking can vary not only by heel height but also by heel area. In case of wearing high heels with the narrow heel area, the peak GRF_{AP} occurred in early loading response period than wearing high heels with the wide heel area (Table 1(B)). The changed timing of the peak GRF_{AP} can be explained by the fact that the center of pressure of the foot moves quickly from the rearfoot to the forefoot in the forward direction due to the narrow heel area, and it resulted in the changed timing of the peak uCOF and the increased peak uCOF by the reduced GRF_V (Table 1(A) and (C)). In summary, the resultant shear force reaches the peak quickly by the fast forward roll-over of the foot before the vertical force is sufficiently large with weight acceptance, and this changed gait patterns increase the peak uCOF during high-heeled walking with narrow heel area. The reduced stance ratio (Table 2) is also related to the fast forward roll-over of the foot (correlation analysis, $r = 0.650$, $p < 0.001$) since the fast foot roll-over brings quick toe-off and induces short stance time.

The peak uCOF when wearing the wide heels was 0.209 and the peak uCOF increased to 0.225 by about 0.02 when wearing the narrow heels (Table 1(A)). Beschorner et al. have reported that a small difference in uCOF can increase the probability of a slip dramatically, showing a slipping odds ratio of 1.7 for an increase of 0.01 in uCOF [8]. According to the logistic regression result in the study of Beschorner et al., the uCOF of 0.2 shows 25% of probability for slipping during walking on a floor having aCOF of 0.165, while the uCOF of 0.22 shows 50%. It implies that wearing narrow high heels can induce two times more slipping than wearing wide high heels during walking on the floor having aCOF of 0.165 due to the increase in the peak uCOF from 0.209 to 0.225. Wearing narrow high heels should be carefully concerned during walking on surfaces having low aCOF since it can increase the risk of slipping.

In this study, the walking experiments were conducted on the treadmill at the specified speed. The effect of the heel area on uCOF at the self-selected speed may be different from the results of this study if the walking speed is significantly affected by the heel area.

5 Conclusion

This study presented that the heel area of high heels influences on the uCOF during walking at an identical walking speed even with the same heel height. Wearing high heels with a narrow heel area increases the peak uCOF since the peak uCOF occurs in early loading response period and the vertical GRF is not sufficiently large at the timing of the peak uCOF. Wearing high heels with a wide heel area is recommended for women to reduce the peak uCOF and the risk of slipping.

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