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Floor Slipperiness Effect on the Biomechanical Study of Slips and Falls

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Abstract

A study was conducted to find the possible relationship between slip distance and dynamic coefficient of friction (DCOF) through the biomechanical study of slips and falls using a broader variety of floors and levels of slipperiness than those used before. Four different floor surfaces covering the full range of floor slipperiness (with and without an oil contaminant) were prepared for ten subjects with each walking at a fixed velocity. The results showed that slip distance and heel velocity had a decreasing trend while stride length had a increasing trend as DCOF increased. The contaminant effect overpowered floor slipperiness effect because a higher DCOF surface with oil contaminant created longer slip distance than the lower DCOF with dry floor. Normal gait pattern and suggested heel velocity (10 to 20 cm/sec) were seen on dry floors but abnormally longer stride length and 5 to 10 times faster heel velocity were found on oily floors. In other words, faster heel velocity (greater than 10 to 20 cm/sec) is recommended to measure DCOF on oily floors because the assumption of normal gait was no longer valid.

1. INTRODUCTION

Slips and falls on the same level while carrying objects are common accidents in industrial work places. To reduce these accidents, the biomechanical and tribological approaches have been mainly used.

The biomechanical approach has been used to investigate the human reactions to slips and falls. Slip distance has been used to investigate the floor slipperiness effect [13], and has shown promise as a good parameter to

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represent floor slipperiness by the inverse relationship with static coefficient of friction [7]. The heel velocity at heel strike was critically related to the occurrence of slips and falls and resulted in one of the essential parameters for governing slips and falls [11, 14]. The range for the heel velocity at heel strike was shown to be 10 to 20 cm/sec for a normal gait [9] and increased up to 50.8 cm/sec during a slip [14]. Stride length was measured to investigate the gait pattern changes with respect to different floor slipperiness [14]. In general, stride length decreased while cadence increased as floor slipperiness increased.

For a tribological study, static and dynamic coefficients of friction, and measuring devices have been studied. Static coefficient of friction (SCOF) has been used commonly but dynamic coefficient of friction (DCOF) has shown theoretical superiority related to the human biomechanics of slips and falls. To measure DCOF, the biomechanical study has provided the important parameters (heel velocity, vertical force, and shoe angle) of human biomechanics related to slips and falls, which were later classified into the biomechanical factors by Redfern and Bidanda [8]. They also classified shoe material, floor type, and contamination into the environmental factors. They investigated the effects of environmental and biomechanical factors on DCOF measures. The range of the testing heel velocity was 10 to 20 cm/sec to represent levels seen during a normal gait. They found that heel velocity had the largest effects on the DCOF. Among environmental factors, contaminants were found to be an important factor.

As mentioned so far, biomechanical and tribological approaches have been reasonably reliable measures for the floor slipperiness study. However, the biomechanical approach has concentrated too much on the details of human biomechanics and therefore has been used on only a limited number of floor surfaces and floor conditions [5, 13, 14]. Another critical problem in the biomechanical approach is that it has provided many significant parameters to the study of slips and falls but it has never provided a uniquely accepted parameter comparable to DCOF in the tribological approach. On the other hand, the tribological approach has tried to simulate human biomechanics of slips and falls with slip-resistance testers but the subtle human reactions have not been copied exactly by these testers, and this has resulted in an over-simplification of DCOF measures. Furthermore, the selection of important biomechanical factors applied to measure DCOF in the tribological approach has been based on biomechanical studies limited in scope relative to the levels of floor slipperiness studied. In other words, adequate human biomechanical reactions to slips and falls have not been sufficiently studied to provide a basis for the tribological approach for measuring DCOF.

Based on the findings above, the biomechanical slip distance has already shown promise to represent floor slipperiness by the inverse relationship with SCOF. However, even with theoretical superiority, DCOF has not been used to investigate the relationship with the biomechanical slip distance to represent floor slipperiness. Therefore, this study was conducted to investigate the availability of the biomechanical slip distance in representing the floor slipperiness. The biomechanical study of human reactions itself in this study provided the basic set up values for the measure of tribological DCOF because this study was carried out with a wide range of the floor slipperiness. Another objective of this study was to investigate the oil contaminant effect to find the degree of significance to the floor slipperiness for the biomechanical approach because the contaminant effect was found to be significant for DCOF measures in the tribological approach [8].

2. METHOD

2.1 Subjects

Ten male university students participated in this experiment. The mean height was 179.3 cm (±7.10), and ranged from 170.2 to 190.5 cm. The mean weight was 74.2 kg (±7.58) with a range of 60 to 80 kg. The mean age was 24.9 (±4.77), ranging from 19 to 35 years old.

2.2 Apparatus

Four different floor materials were chosen for the experiment : plywood, ceramic tile, vinyl tile and stainless steel plate. The dimensions of the simulated floor were 250cm × 30cm × 2.5cm. Sixteen ceramic tiles (15cm × 15cm), eight vinyl tiles (30cm × 30cm), and a sheet of stainless steel plate were mounted on a piece of plywood. The simulated floors were mounted in a shallow pit, so that the floor surface height would be leveled with the laboratory floor and no trapping hazards would exist. To reduce the visual effect of floor materials, the color and contrast for all floor materials were similar.

A container (46 cm × 30 cm × 30 cm), which was made with 1.3 cm thick plywood and weighed 10 kg, was used for the carrying task. Lead bars were arranged at the center area of the plywood container to control the symmetric weight distribution. The container had 15.2 cm handles on both sides to make it easy to carry. In addition, a supporting strap was attached to both sides to protect the container from falling onto the subject.

For the collection of three-dimensional biomechanical data, the ExperVision motion analysis system was used. The motion analysis system consists of three video cameras, a video recorder, a digitizer, a monitor, a SUN SPARC workstation, and the software for target tracking and data analysis. This system provides a data collection rate of up to 200 Hz. However, past experiments have shown that 60 Hz was adequate for gait analysis [5, 7, 13].

In order to protect subjects from falling during the experiment, a fall arresting rig [3] was used. The overall function of the system is to allow a subject, wearing a full-body harness, to walk under experimental conditions with little or no restrictions. Whenever an imbalance is detected, the system immediately arrests the fall and discontinues its motion.

2.3 Floor and Load Conditions

A programmable slip resistance tester was used to measure the DCOF [1]. The tests were conducted at 15 cm/sec for heel velocity with a vertical force of 9 kg. For oily condition, a high viscosity oil (SAE 30) was used to simulate a contaminated industrial floor condition. Four selected floors were : oily vinyl tile (DCOF = 0.11); dry stainless steel (DCOF = 0.27); oily plywood (DCOF = 0.43); and dry ceramic tile (DCOF = 0.57).

Five different load carrying levels were chosen based on the percentage of body weight and fixed load weight methods. For the percentage of body weight, 40 percent of body weight was the recommended maximum carrying weight by Cathcart et al. [2] so that 20 and 40 percent of body weights were chosen. For the fixed load weight method, 18 and 24 kg were chosen because 18 kg is most typically found as the maximum in grocery stores and industrial environment and 24 kg was recommended as the maximum acceptable weights of carry (MAWC) for 90 percent of the industrial male workers by Snook [12]. No external load was also included.

2.4 Procedure

To analyze the subject's movement, retro-reflectors were attached to the anatomically significant body positions defined by Winter [17] : heel, toe, ankle (lateral malleolus of fibula), knee (lateral femoral epicondyle), and hip (greater trochanter) of the subject's left side. All subjects wore the same shoes (available in a variety of sizes) with a PVC sole to have consistent frictional values. Prior to these experiments, each subject was given an opportunity to walk around the laboratory to familiarize himself with the task at the pace of his normal walking speed. The equipment layout is shown in Figure 1. The walkway track was circular, with a circumference of approximately 25 m. The simulated floors were placed in a 2.5m straight section of the walking track.

For the experiment, a fall arresting system was used to protect subjects from a possibly dangerous fall. The normal walking speed for male adults (20 to 59 years old) was reported at 1.36 m/sec by Waters et al. [15]. The speed of the fall arresting rig, therefore, was fixed at 1.33 m/sec instead of 1.36 m/sec because 1.33 m/sec is the closest velocity to the normal walking velocity the rig could create.

Subjects were then asked to walk across the floor samples while wearing a harness attached to the fall arresting rig. Data collection was started right after subjects crossed the photo cells and lasted for 3 seconds. Right before the left side photo cell in subject's direction of progression, a foot print was placed for subjects

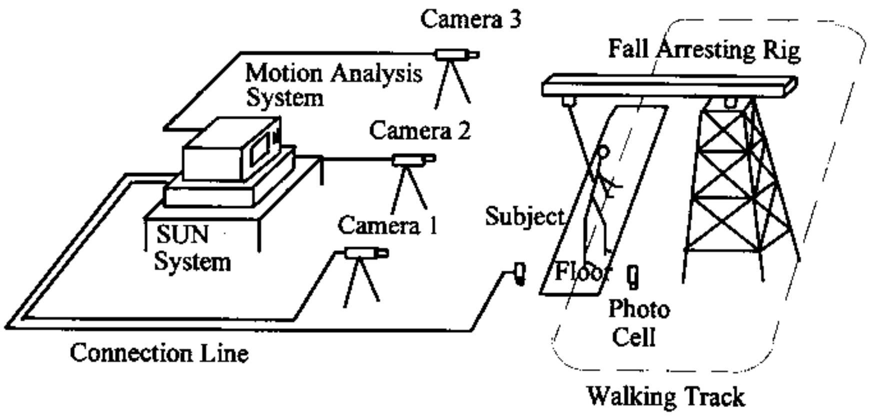

Figure 1. Equipment Layout

to step on with the left foot. Subjects stepped on the arranged floors with their right foot after crossing the photo cells.

Ten combinations (5 load levels x 2 replications) of the load carrying conditions were totally randomized within each floor surface. Subjects were allowed to walk freely without any arm movement restrictions with no external load. Each subject had 40 (4 floors x 5 load levels x 2 replications) trials of walking for this study. The floor samples were arranged so that each subject walked on a floor surface with the left foot on the left surface and the right foot on the right surface.

To reduce the learning effect, each subject walked on only one floor per day with at least one day break between experiments. A subject took a total of four days to complete this experiment. Subjects were run on dry floors prior to oily floors according to the experimental design. Each subject, therefore, walked on each of the randomized dry floors and then moved to each of the randomized oily floors. Before walking on each oily floor surface, a high viscosity oil (SAE 30) was brushed on the left floor surface before each walk to achieve the same viscosity. While the subjects were walking along this path, they were instructed to keep their eyes on the front wall and to try to maintain the walking speed that they practiced.

2.5 Experimental Design and Biomechanical Data Analysis

For the statistical analysis, the variance-component model for the repeated measures with factorial design was used with subjects as a random block term [16]. With the variance-component model, the insignificant random interaction terms could be removed from the full model to give more power to the tests for the fixed terms. With no significant main interaction effect, the Student-Newman-Keuls (SNK) multiple comparison test was performed to classify the main treatment levels. However, a contrast with Fisher's least significant difference (LSD) was used if there were a significant main interaction effect.

For this study, three dependent variables were chosen : slip distance, stride length, and heel velocity. The slip distance was considered as the distance between slip-start and slip-stop points [13] and was identified by plotting the vertical coordinates versus the horizontal coordinates of the heel of the stance phase. The slip-start was normally identified as the point at which a change of the horizontal displacement continued at constant position in the vertical axis. The slip-stop was defined as the point at which a change in vertical axis occurred, without a change of the horizontal axis. Figure 2 shows the x-y plot of typical heel movement before and after heel contacted the floor surface including the slip-start and slip-stop points.

Since the slip does not have to be in a straight line, slip distance has to accommodate the lateral component and the resultant slip distance is as follows :

Slip distance = $((X_2 - X_1)^2 + (Z_2 - Z_1)^2)^{1/2}$

where the coordinate of the slip-start is (X_1, Y_1, Z_1) and the coordinate of the slip-stop is (X_2, Y_2, Z_2). The X, Y, and Z axes represent the horizontal, vertical, and lateral directions, respectively (Figure 3). The slip-start point was defined as the first minimum of the vertical velocity of the heel after the heel struck the floor. Theoretically, this value was zero or a

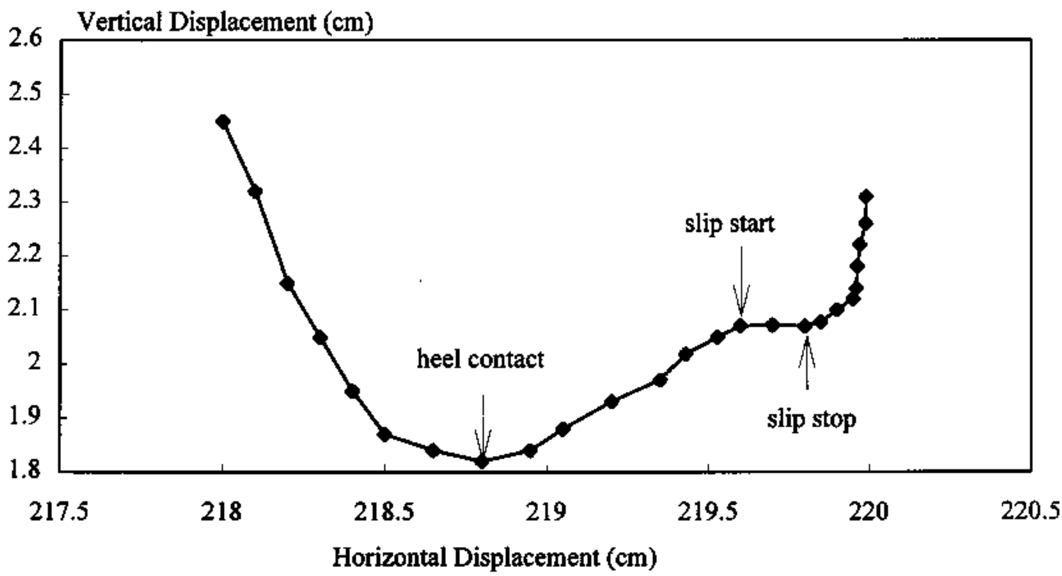

Figure 2. Typical Heel Movement around the Heelstrike (Son, 1990)

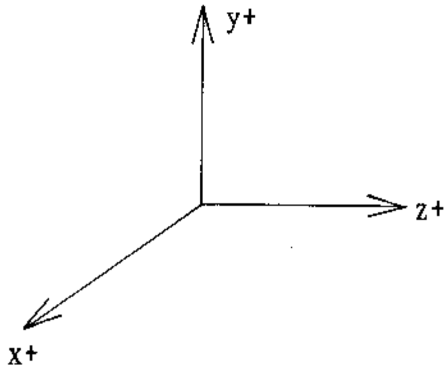

Figure 3. Sign Convention for Each Coordinate

close-to-zero number was expected. The slip-stop point was defined as the first minimum of the horizontal velocity of the heel after slip-start point. This number was also expected to be small.

The velocity of the heel at the heel strike on the floor was measured. The point of the heel contacting the floor in Figure 2 was defined as the lowest point in vertical direction of heel movement. Resultant heel velocity at the point of heel contact was calculated by the following definition.

Heel velocity = $(V_x^2 + V_z^2)^{1/2}$

where V_x and V_z are the heel velocities in the horizontal and lateral directions, respectively. To calculate the heel velocity for each direction, the finite differentiation method was used [17]. That is, the difference of the foot displacements of 1/60 second before(X_{i-1} or Z_{i-1}) and after (X_{i+1} or Z_{i+1}) the heel strike was divided by the elapsed time (2$\triangle$t). By doing so, the line joining X_{i-1} to X_{i+1}(or Z_{i-1} to Z_{i+1}) has the same slope as the line drawn tangent to the curve at X_i.

$$V_X = \frac{X_{i+1} \quad X_{i-1}}{2\triangle t} \quad or \quad V_z = \frac{Z_{i+1} \quad Z_{i-1}}{2\triangle t}.$$

Stride length was defined as the linear distance in the direction of progression between successive points of foot-to-floor contact of the same foot [6] so that it was measured from the second step (the left foot) to the next contact of the left foot. The stride length was calculated from the difference between consecutive positions of the heel contacting the floor.

3. RESULTS AND DISCUSSION

The ANOVA test for the full model was first performed to find the insignificant random interaction effect and then the ANOVA test for the reduced model was again performed after removing the insignificant random interaction terms. The results are shown in Table 1. The empty cells in Table 1 represent the insignificant random interaction terms for the full model. No further investigation for the SUBJ-related random interaction terms was made because the analysis of the SUBJ-related random terms was not great concern in this research. The significance levels for all tests were set at 0.05.

Since the main interaction term (DCOF* LOAD) for slip distance was highly significant with p-value = 0.0178, the interaction plot was necessary to investigate where the interaction was from. The p-value for heel velocity

Table 1. ANOVA summary with p-values

Sources	dof	Slip Distance	Stride Length	Heel Velocity
DCOF	3	0.0001	0.0001	0.0001
LOAD	4	0.0001	0.0001	0.0002
DCOF*LOAD	12	0.0178	0.3735	0.1334
SUBJ	9	0.0599	0.0001	0.0851
SUBJ*DCOF	27	0.0001	0.0001	0.0001
SUBJ*LOAD	36	-	-	0.3042
SUBJ*DCOF*LOAD	108	-	0.0009	-

The dof represents degree-of-freedom.

(0.1334) was not significant based on the significance level of 0.05 but the interaction plot might be helpful to understand where the interaction came from because the rule of thumb of assuming no significant interaction effect is to have the p-value greater than 0.25. Therefore, Figure 4 was drawn for the detailed investigation. A p-value for stride length was found to be insignificant so that the SNK multiple comparison test was performed to find the significant treatment levels.

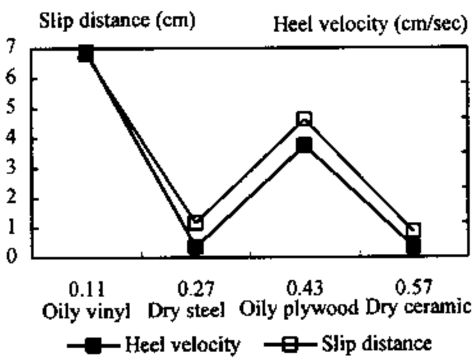

Figure 4. Interaction Plot for Slip Distance and Heel Velocity

Figure 4 shows an inconsistent trend of slip distance as DCOF increased. The origin for the inconsistency was found to be very obscure. This inconsistency might be from unexplainable interaction with a PVC sole or different penetrability of oil contaminant (SAE 30) into different materials or the mechanical problem of slip resistance measuring device [1] itself. Therefore, detailed investigations of the above unexplainable interaction should be preprocessed before the study of the availability of the biomechanical slip distance to represent floor slipperiness. The same trend for heel velocity is also shown in Figure 4 even with the insignificant interaction with p-value = 0.1334 based on the significance level of 0.05. This inconsistency caused the significant interaction for slip distance and heel velocity so that the interpretation of the main effect tests might be meaningless. Therefore, the contrast analysis was introduced to investigate the floor slipperiness effect mixed with significant interaction.

Table 2 shows the summary for the contrast

Table 2. LSD groups for slip distance (unit : cm)

Floor	DCOF	No Load		Other Loads	
		Mean	LSD	Mean	LSD
Dry ceramic	0.57	0.27	A	0.41	A
Dry steel	0.27	0.28	A	0.45	A
Oily plywood	0.43	3.14	B	4.37	B
Oily vinyl	0.11	4.97	B	8.80	C

analysis with slip distance. Two separate analyses should be applied to the floor slipperiness effect for slip distance for no external load and the other load levels because inconsistent groupings were found. At other load levels, three significantly different groups were classified. No difference was found between dry ceramic and dry steel. Oily plywood created significantly longer slip distance than dry ceramic and dry steel. Slip distance for oily vinyl was found to be significantly longer than any other floors. At no external load level, slip distance for group A (dry steel and dry ceramic) was significantly shorter than slip distance for group B (oily plywood and oily vinyl).

According to Table 2, a contaminant effect was shown to be significant because the dry surfaces were grouped together regardless of load carrying levels. Oily floors were also grouped together at the no external load level but were significantly different from each other at the other load levels. Therefore, contaminant effects of floor slipperiness were investigated with the "dry versus oily" contrast.

As a result of the contaminant effect, oily surfaces created significantly longer slip distance (6.08 cm) than dry surfaces (0.40 cm). Slip distance for dry floors was considered as microslips, which subjects were not able to detect. However, slip distance for oily floors was classified as slips, which subjects were well aware of slipping and took corrective action of various forms in order to arrest the slip. Oily surfaces, therefore, resulted in the exposure to more dangerous slips than dry surfaces. The contaminant effect even overpowered the inherent floor slipperiness because a higher DCOF surface with oil-contaminated plywood created longer slip distance than the lower DCOF dry steel floor. Of course, the oil contaminant affected the floor slipperiness, but the effect was greater than expected.

For stride length, since the main interaction effect was not significant, the SNK multiple comparison tests were performed to differentiate main treatment levels and the results are shown in Table 3. Stride lengths for dry steel and dry ceramic were grouped together even with a big floor slipperiness difference based on tribological DCOF. The remaining two surfaces (oily plywood and oily vinyl) were

Table 3. SNK test for stride length (unit : cm)

Floor	DCOF	MEAN	SNK
Dry ceramic	0.57	144.2	A
Dry steel	0.27	144.0	A
Oily plywood	0.43	137.1	B
Oily vinyl	0.11	133.7	B

classified into group B, which is significantly different from Group A. From Table 3, there existed an obvious contaminant effect because dry and oily surfaces had separate SNK groups. Therefore, contaminant effects of floor slipperiness could be confirmed with the "dry versus oily" contrast. As expected, stride length for dry surfaces (144.11 cm) was significantly longer than stride length for oily surfaces (135.36 cm).

As a result of the analysis of stride length, stride lengths for dry ceramic and dry steel were consistently grouped together and were considered as a normal gait pattern [15]. Subjects reduced their stride length to have better stance on oily floors. Subjects decreased stride length about 9 cm for oily floors compared to stride length for dry floors. This decreased stride length for oily floors considered as an abnormally short gait pattern. Stride length was also found to be dependent on slip distance and cadence. As floor became more slippery, stride length decreased but cadence increased to maintain the fixed walking velocity. However, the main reason for the stride length decrease was because of different floor slipperiness. That is, stride length was found to be mainly dependent upon floor slipperiness, resulting in abnormal gait for oily floors. Of course, the normal gait was shown on dry floors.

As shown for slip distance so far, the analysis for heel velocity utilized the same procedure. The summary for the significantly different heel velocity groups for DCOF is presented in Table 4. At no external load level, two significantly different groups were classified. Group A (dry steel and dry ceramic) had a significantly slower heel velocity than group B (oily plywood and oily vinyl). At the other load levels, three significantly different groups were classified. Oily vinyl had the fastest heel velocity and was significantly different from the other floor surfaces. Oily plywood had the second fastest heel velocity and was also significantly different from the other floor surfaces. Dry steel had a little faster heel velocity than dry ceramic but no significant difference was found between dry steel and dry ceramic.

The contaminant effect of floor slipperiness for heel velocity was also investigated. Heel velocity for oily floors (108.90 cm/sec) was found to be significantly faster (about 5 times

Table 4. LSD groups for heel velocity (unit : cm/sec)

Floor	DCOF	No Load		Other Loads	
		Mean	LSD	Mean	LSD
Dry ceramic	0.57	10.2	A	19.3	A
Dry steel	0.27	14.1	A	25.9	A
Oily plywood	0.43	66.9	B	92.2	B
Oily vinyl	0.11	93.5	B	139.9	C

faster) than heel velocity for the dry floor (20.49 cm/sec). This big heel velocity difference between dry and oily floors had already been identified that subjects tried to land the leading foot as quickly as possible to compensate the body instability due to oily floors [13]. This fast landing of the leading foot produced fast heel velocity on oily floors. Another reason for this heel velocity difference was a fixed walking velocity created by the fall arresting rig. With a fixed walking velocity, cadence increased as stride length decreased. With this increased cadence, heel velocity is easily expected to increase right before the heel contacts the floor surface. This increased heel velocity right before the heel strike affected the landing velocity of the leading foot. The fall arresting rig also affected the body instability on oily floors because the fall arresting rig did not give enough time for subjects to modify their gait pattern according to oily floors.

Heel velocity was found to be matched with the suggested range of heel velocity for DCOF measures [10]. Heel velocity range between 10 to 20 cm/sec was preferred because the testing velocity should be at levels during normal gait not after a slip has already occurred. From this study, heel velocity on dry floors was within the preferred range. However, heel velocities for oily plywood and oily vinyl were found to be much faster than the suggested heel velocity range [10] and even faster than heel velocities for slips (50.8 cm/sec) by Strandberg and Lanshammar [14]. Heel velocities for oily floors were twice as fast as heel velocities for slips [14], and even 5 to 10 times faster than the suggested heel velocity ranges by Redfern et al. [10]. This implies that the normal gait assumption was not true when subjects walked on oily floors. Based on previous research, stride length and/or cadence should be modified to reduce walking velocity in order to have a more stable posture on oily floors. In other words, a faster transfer of the body weight from one leg to the other could be accomplished as stride length decreased [4]. In this study, with a fixed walking velocity, stride length decreased as the subject encountered a contaminated surface. With the decreased stride length, abnormal gait patterns were found when walking on oily floors. The suggested HV between 10 to 20 cm/sec by Redfern et al.[10] was appropriate to measure DCOF on dry surfaces. For oily surfaces, heel velocities between 60 to 140 cm/sec were encountered based on a fixed walking velocity.

4. CONCLUSIONS

The conclusions of this study can be summarized as follows.

1. The study of the availability of the biomechancial slip distance to represent floor slipperiness should be followed by the detailed investigation of the inconsistency between DCOF and the biomechancial slip distance because this inconsistency might be from unexplainable interaction with a PVC sole or different penetrability of oil contaminant (SAE 30) into different materials or unreasonable set up values for slip resistance measuring devices or the mechanical problem of slip resistance measuring device [1] itself.
2. No normal gait was found on oily floors because subjects reduced their stride length to have a more stable stance on oily floors. Therefore, the assumption of the normal gait in measuring DCOF is not applicable to oily floors. In other words, faster heel velocity is recommended because heel velocity of 10 to 20 cm/sec was too conservative and unrealistic for oily floors.
3. The contaminant effect was found to be significant enough to overpower the floor slipperiness effect because a higher DCOF surface with oil-contaminated plywood created longer slip distance than the lower DCOF dry steel floor. This finding confirmed the importance of the contaminant for the study of slips and falls in the biomechanical approach as well as the tribological approach.

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95년 11월 최초 접수, 96년 5월 최종 수정