Title	Lower extremity gait kinematics on slippery surfaces in construction worksite		
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Running title	Gait kinematics on slippery surfaces		

ABSTRACT

Purpose: The purpose of this study was to investigate the lower extremity kinematics when walking on potential slippery surfaces in simulated construction worksite environments. **Methods:** A survey was conducted to select two footwear, two floorings and four contaminants to represent the local construction worksite environments and made sixteen simulated conditions. A mechanical slip resistant test was conducted to evaluate the slipping potential of the sixteen conditions by the value of dynamic coefficient of friction. The sixteen conditions were classified into three groups by slipping potential. Fifteen Chinese harnessed male subjects were instructed to walk and avoid slips on each of the sixteen simulated five-meter walkways ten times at their natural cadence. The movements in sagittal plane were videotaped, digitized and analyzed by motion analysis system. Gait pattern parameters were obtained. Lower extremity kinematics data were time-normalized from foot strike (0% stance) to take off (100% stance), and were extracted from foot strike to mid-stance (50% stance) at 10% stance intervals. **Results:** ANOVA showed that with increased slipping potential, changes in gait pattern parameters included increased stance and stride time, shortened stride length, decreased propagation speed and gentle heel strike. In lower extremity kinematics parameters, significant differences were found mainly at ankle joint rather than at knee joint. **Conclusion:** Strategy to prevent slips included increased stance and stride time, shortened stride length, decreased propagation speed and gentle heel strike. Ankle joint played the most important adaptation strategy. Such strategy included to reduce range of motion, to maintain a stiff joint, to achieve flat-foot landing or plantar-flexed ankle joint during the first 10% stance. **Key Words:** Occupational slips and falls, injury prevention, gait adaptation, slipping potential measurement.

INTRODUCTION

Paragraph Number 1 Slips and falls are among the most serious causes of morbidity and mortality (7). In the United States, slips and falls were associated with disability, fractures and deaths in occupational area (16). In the United Kingdom, about 20% of the occupational injuries are reportedly due to slips and falls each year (7). In Hong Kong, data from local hospitals in 1999 showed that industrial section ranked top (30.1%) in the causes of traumatic injuries, and accidental falls was the main cause (41.1%) of hospitalized injuries (11). In 2000, slips and falls was the most popular cause in occupational accidents, contributing to 25% of the total cases (12).

Paragraph Number 2 Slips and falls were involved by complex extrinsic environmental factors and intrinsic human factors (4). In normal non-slippery environment, the extrinsic and intrinsic factors were in balance, resulting in an average low slipping potential. When the extrinsic environmental factors become more likely to introduce a slip, human could modify the intrinsic human factors in order to restore a low slipping potential and finally reduce the overall slipping likeliness. The cumulative effects of the risk factors mentioned above can be illuminated by kinetics and kinematics measurement. In kinetics, the dynamic coefficient of friction (DCOF) was commonly investigated. It was because the heel horizontal velocity was not zero at the moment of heel strike (5) and thus DCOF instead of the static coefficient of friction (SCOF) was believed to be more relevant to slip events (15). Various mechanical slip resistant tests were conducted to investigate the slipperiness of walking surfaces by analyzing the dynamic coefficient of friction between combinations of footwear and walking surfaces (5,9,13).

Paragraph Number 3 In kinematics, most of the previous studies investigated the changes of gait parameters during the heel contact phase. Increased step length would result in a greater shear force, which in turn increased the slippery likeliness (3). In adapting to slippery walking surfaces, people of all ages used to shorten the step length to reduce the likelihood of slipping (5,7). During walking, heel horizontal velocity rises gradually after take-off of the foot, reaches a maximum during the swing phase, and falls to zero rapidly after heel contact to support the stance leg (6). Failure to achieve zero horizontal velocity at heel contact may result in a slip. However, in slowing down the walking speed, the heel horizontal velocity was not decreased as expected (17). Therefore, heel velocity should be reported in gait analysis. In lower extremity kinematics, the overall profiles of ankle and knee joint angles were in agreement across the past studies (1,18). At ankle, there is a dorsiflexion at heel contact, followed by a rapid plantar flexion. At knee, there is a flexion during the first 30% of the stance, and another flexion again during the last phase of the stance, followed by take-off of the foot (14).

Paragraph Number 4 Injuries due to slips and falls are not purely random events but rather predictable with known risk factors (4). A local survey (10) reported that 48.7% of the construction workers believed that these injuries can be prevented by working with proper safety equipments, policies and measures. However, about 34% of the workers found difficulties in learning about the safety measures to prevent occupational injury. The purpose of this study was to investigate the lower extremity preventive measures to slips when walking over potential slippery walking surfaces in simulated construction worksite environments. The findings from this study would help discovering the risk factors, understanding human adaptation to slippery walking surfaces, and educating the construction worksite workers to take safety walking strategy when walking on slippery surfaces in order to prevent occupational slips and falls.

METHODS

Paragraph Number 5 **Survey.** Two thousand questionnaires were randomly sent to local construction site workers. The survey aimed to get statistics figures about the popular footwear used by the workers, the nature of the walking surface in construction site, and the most common types of contaminants on the walking surface, in order to better simulate the real situation in local construction worksites. The selection criteria of the footwear, flooring and contaminants were the items with top rank and comparable popularity. From the results of the survey, two types of footwear, two types of flooring surface and four types of contaminants were chosen. The most popular type of footwear (93.9%) was a kind of safety shoe which passed the European Safety standard EN 345, and is currently recommended by the Hong

Kong Occupational Safety and Health Council. The second popular type of footwear was cloth shoe, which was a kind of light-weight, low-price, traditional sport shoe in Hong Kong and Mainland China. Even the second popular shoe, the cloth sport shoe (2.0%) was far less popular than the safety shoe, it was also chosen for comparison. The two most popular types of flooring surface included cement plates (57.3%) and wooden plates (33.3%) were chosen as they had comparable popularity. The four selected contaminants conditions included dry, sand (43.4%), water (38.7%) and oil (33.3%). The selected footwear, flooring and contaminants from the results of survey made a total of sixteen simulated construction worksite environments to be investigated.

Paragraph Number 6 **Mechanical slip resistant test.** The dynamic coefficients of friction (DCOF) of all sixteen footwear-flooring-contaminant conditions were measured for slip resistant classification. A self-designed pulley system (Figure 1) which allowed an adjustable horizontal drag force was used to drag a 11.8 kg-weighted shoe over a testing flooring surface ten times over a force plate (Kistler 9281CA, Switzerland) (9). Weights were added in the pulley system to increase the horizontal drag gradually until the shoe slid. The sliding velocity, horizontal and vertical reaction forces during the slide were recorded by the force plate. The DCOF was calculated by dividing the horizontal reaction force by the vertical reaction force. According to the measured DCOF and the classification scale suggested by Grönqvist (5), the sixteen conditions were classified into three groups (very slip-resistant, unsure, slippery) as shown in Table 1. The effect of slipping potential on the lower extremity kinematics parameters were investigated in latter human walking test.

Paragraph Number 7 **Subject.** Fifteen Chinese males (age = 21.8 ± 1.3 years, mass = 64.5 ± 4.6 kg, height = 1.75 ± 0.06 m) with no gait abnormalities and with right legs as their dominant legs were recruited in this study. Written informed consents were obtained from all subjects before the study. The university ethics committee approval was received for the study

Paragraph Number 8 **Instrumentation.** A harness system was installed by attaching a harness (Protecta International AB103, USA) which conformed to the European safety standard EN 361 to a horizontal stainless steel wire by a adjustable connection lanyard (Protecta International AL110C, USA) and a steel safety hook (Protecta International AJ501, USA) which conformed to the European safety standard EN354 and EN362 respectively. The horizontal stainless steel wire was 32 feet in length, and was firmly attached on the wall

2.4 meters from the ground at both ends. A pair of safety shoes with size 42 (length = 265mm) which conformed to the European safety standard EN 345 were purchased from a local distributor recommended by the Hong Kong Occupational Safety and Health Council. The shoe sole of the safety shoe fully complied with the main regulations provided by the EEC/89/686 European Directive with harmlessness, comfort, solidity, and protection against skidding risks (UNI 8615/1 – DIN 4843). Cloth sport shoe of same size was purchased from sport equipment shops. The cloth sport shoe was made with thin layer of cloth shoe last, and with thin and flexible rubber shoe sole. A five-meter walking path was prepared by connecting several cement or wooden flooring plates provided by the university construction work unit. The amounts of the contaminants were about 1 L/m^2 for sand, and 0.5 L/m^2 for water and oil, as they could form a thin layer on the flooring surface without spilling out of the surface. Oily condition was prepared with motor oil (elf 10W40 motor oil) which was often used in engines and machines in construction sites (1,6).

Paragraph Number 9 **Procedure.** Subjects were requested to dress in black and tight clothing, which together with illuminated silvery reflective skin markers facilitated the auto-digitizing process in video data analysis. The reflective skin markers were attached at the major lower extremity anatomical landmarks on right side, including the greater trochanter, lateral femoral condyle, lateral malleolus, fifth metatarsal head and talus (Figure 2). Ankle and knee joint angles were defined as the included angles (Figure 2). Harness system was adjusted for each subject so that it would not affect the subject's normal gait as perceived by the subject, and it could arrest and protect the subject in case of a fall (Figure 3). For both cement and wooden walking surfaces, each subject performed ten trials of walking on each footwear-flooring-contaminant condition in the sequence of dry, sand, water and oil. The sequence was designed to avoid the gait alternation effect when walking on dry surface after slippery surface as suggested by previous study (2). During each trial, subject was instructed to walk at a self-paced normal speed and avoid slipping.

Paragraph Number 10 One CCD digital video camera (JVC 9600, Japan) with 50Hz filming rate at 1/250s shutter speed was used for videotaping the human motion in sagittal plane. The filmed data were processed by motion analysis system (Ariel Performance Analysis System, USA) to obtain two-dimensional coordinates and their derivatives of digitized anatomical markers. Trials with slips were discarded. A slip was defined as when the subject required support from the harness as reported by the subject, or when the heel horizontal velocity failed to achieve zero within a three centimeters displacement range (8) immediately after the foot strike (2), which was checked by motion analysis.

Paragraph Number 11 **Data analysis.** Data of the successful trials of walking without slips were averaged for each footwear-flooring-contaminant condition. Gait pattern parameters including stance, swing and stride time, stride length, heel horizontal and vertical velocity and acceleration at foot strike, and mean propagation speed were obtained from motion analysis system. Mean propagation speed was measured by the average value of horizontal forward linear velocity of the hip during the stance period. Lower extremity kinematics data including angular displacement and velocity of ankle and knee joint, and the foot-floor angle were extracted. The profiles of these data were time-normalized from foot strike (0% stance) to take off (100% stance), and were evaluated at from foot strike (0% stance) until mid-stance (50% stance) with 10% stance intervals in between. One-way multivariate analysis of variance (MANOVA) with repeated measures was employed to examine the difference in gait pattern parameters and lower extremity kinematics data between the classified slip resistant groups. One-way analysis of variance (ANOVA) was employed to examine the difference in each gait pattern parameter and in each lower extremity kinematics data at selected time points between the groups. Significance level was set at $p < .05$ level. Tukey post-hoc pairwise comparisons were conducted between each pair of groups when significant differences reached $p < .01$ significance level.

RESULTS

Paragraph Number 12 **Gait pattern.** MANOVA showed that gait pattern was significantly affected by the walking surface slipperiness ($p < .05$). The descriptive statistics and the results of ANOVA and Tukey tests were showed in Table 2. Results showed that when the walking surface slipperiness increased from “very slip-resistant” to “unsure” and “slippery”, the stance time and stride time significantly increased by about 0.13s (16%) and 0.14s (12%) respectively ($p < .01$). Stride length and mean propagation speed significantly decreased from 1.22m to 1.06m and from 1.01ms^{-1} to 0.80ms^{-1} respectively ($p < .01$). Heel horizontal velocity and vertical acceleration showed significant decrease in magnitude in slippery condition ($p < .01$). Heel horizontal acceleration showed significant decrease in magnitude in slippery condition at $p < .05$ level. No significant difference was found among groups in heel vertical velocity at $p < .05$ level.

Paragraph Number 13 **Ankle joint kinematics.** MANOVA showed significant differences among different classes on ankle joint kinematics ($p < .01$). The descriptive statistics and the results of ANOVA and Tukey tests were showed in Table 3. The profile of the ankle angle and angular velocity from foot strike (0% stance) to mid-stance (50% stance) for the three classes were shown in Figure 4. Similar dorsiflexion trends were found from foot strike to mid-stance in all three groups. The range of angle changes for the three groups were similar, about 20 degrees from foot strike to mid-stance. Generally, the included ankle angle in “unsure” group was significantly larger than the other two groups at all selected time points ($p < .05$). Comparing the trends of “slip-resistant” and “slippery” group, the ankle joint in “slippery” group was more plantar flexed from foot strike to 15% stance, and was more dorsiflexed from 15% to mid-stance. However no significant differences were found at all time points. The ankle joint angular velocities were all negative from foot strike to mid-stance, indicating that dorsiflexion occurred all the time in this period. The variation of angular velocity dropped with increasing slipping potential. The range was about 60°/s for slip-resistant group and was about 30°/s for slippery group. Tukey test showed significant differences ($p < .01$) between “very slip-resistant” and “slippery” groups at 10%, 20% and

40% stance.

Paragraph Number 14 **Knee joint kinematics.** MANOVA showed significant differences among different classes on knee joint kinematics ($p < .01$). The descriptive statistics and the results of ANOVA and Tukey tests were showed in Table 4. The profile of the knee angle and angular velocity from foot strike (0% stance) to mid-stance (50% stance) for the three classes were shown in Figure 5. Knee extension occurred during the first 5% stance, and followed by rapid knee flexion until mid-stance. The trends of knee angle and angular velocity of the three groups were similar. No significant differences were found in knee angle at each time point between three groups. For knee angular velocity, significant differences were found between "very slip-resistant" and "slippery" groups from 40% to 50% stance ($p < .05$).

Paragraph Number 15 **Foot-floor angle.** MANOVA showed significant main difference ($p < .01$) on overall foot-floor angle parameters between the three slip resistant groups. The descriptive statistics and the results of ANOVA and Tukey tests were showed in Table 5. The profile of foot-floor angle from foot strike (0% stance) to mid-stance (50% stance) for the three classes was shown in Figure 6. One-way ANOVA showed significant differences at all selected time points ($p < .05$). Tukey pairwise comparisons showed significant difference between resistant-unsure conditions at foot strike, 40% and 50% stance ($p < .05$), between resistant-slippery conditions at 30% and 40% stance ($p < .01$), and between unsure-slippery conditions from 20% to 50% stance ($p < .01$).

DISCUSSION

Paragraph Number 16 Mechanical slip resistant test provided a glance to slipping risk. Based on the dynamic data on human skidding during normal gait published, a value of 0.20 was suggested to be a safe limit for slip resistance (15). Two of the sixteen tested construction worksite environments were evaluated to be having slipping hazard, including wearing either safety shoe or cloth shoe on wooden surface with the presence of oil contaminant. Wooden surfaces are often present in construction worksite when the workers place wooden floorings on top of the finished flooring to protect it against damage and contamination during construction work. Oil contaminants are often present as the workers need lubricant oil for their machines. In the presence of both wooden flooring and oil contaminant, slipping hazard can be implemented, even if the workers wear safety shoe as recommended. Therefore, workers should be more careful when walking on wooden surface, and should at the same time avoid leakage of machine lubricants.

Paragraph Number 17 In this study, the mechanical slip resistant test was not truly realistic because no heel-sole contact was simulated as in previous studies, including the programmable slip resistance tested (PSRT) (13) and Grönqvist’s movable artificial foot (5). However, similar simple mechanical drag test as an alternative low-cost measure was also published (9). The main purpose of this mechanical test was to provide a method to reduce the data groups for latter comparison of kinematics parameters in human walking. It was not the focus of this study and therefore a low-cost protocol which saved time and money was employed in this study. From the mechanical slip resistant test, two out of sixteen conditions were identified to have slipping risk. This made the number of trials for slippery and non-slippery groups unbalanced. However it was the real fact in the simulated environment that most of the conditions were highly slip resistant, and it was a limitation to have comparable amount of trials for different groups for comparison.

Paragraph Number 18 Another limitation was due to the experimental safety measure. In the human walking test, walking with harness was unrealistic but necessary during the experiment in order to arrest and protect the subject in case or a real fall to prevent injury. The harness may provide support to the subject and may alter their normal gait. However the effect of wearing the harness could not be demonstrated as no trials were performed without harness. In order to minimize this effect, the harness was adjusted every time for each subject so that it would not affect the subject's normal gait as perceived. Moreover, the harness may introduce psychological effect to subject as they knew that they will be arrested and will not hit the ground in a real slip.

Paragraph Number 19 Stance time and stride time significantly increased in unsure and slippery walkway conditions, from 0.79s to 0.92s and from 1.21s to 1.35s respectively ($p < .01$). Moreover, with increasing slipping potential, the stride length decreased significantly from 1.22m to 1.06m ($p < .01$). In shortening stride length, the foot could be maintained near the body, and thus increasing the body stability as the line of gravity of the body is closer to the base of support during foot swing. This finding was in agreement with previous published studies (5). In this study, in shortening the stride length, the heel horizontal velocity at foot strike was not significantly decreased as expected. This finding is comparable with Winter's study, which found that the heel horizontal velocity of older adults walking slower was significantly higher than that of younger adults walking faster (17). Significant decrease in mean propagation speed was found ($p < .01$). With increasing slipping risk, the speed decreased from 1.01ms^{-1} to 0.80ms^{-1}. With increasing slipping hazards, the heel horizontal velocity, horizontal acceleration and vertical acceleration dropped significantly ($p < .01$). This indicated a more gentle foot strike in order to prevent a slip. These changes indicated that subjects had employed active strategy in order to adapt to slippery walking surface to avoid slips.

Paragraph Number 20 The profile of ankle joint parameters suggested that dorsiflexion occurred all the time from foot strike to mid-stance in all groups. This finding was not in total agreement with the summary of previous studies of gait kinematics without slipping, which stated that the ankle joint was in slight dorsiflexion at contact, followed by a rapid peak plantar flexion at around 10% of stance as the foot rotated down onto the floor (14). However, the foot-floor angle data suggested that the heel strikes the ground with an angle, and is rotated down onto the floor flat at about 10% of stance, which was in agreement with previous published summarized data (14). The profile of ankle angle in unsure group was found to be significantly higher. It might be due to the uncertainty of the floor slipperiness. The foot-floor angle at heel strike in unsure group was significant smaller. It indicated that subject tended to land on the floor with more flat foot and plantar-flexed ankle joint during the first 10% stance. Flat foot landing may help to achieve a reaction force in normal direction instead of in shear direction by flat foot landing, as the shear force plays important role to initiate slipping. In very slip-resistant group, the angle was quite steady in the first 20% stance, followed by rapid dorsiflexion until mid-stance. The change of ankle angle in slippery group was much steady as reflected by the profile of ankle angular velocity. Such small variations were achieved by maintaining a stiff ankle joint, and may help the subject to better maintain balance and stability on slippery walking surface.

Paragraph Number 21 The knee joint parameters of the three groups showed similar trend and range. At the first 5% stance, there was a small magnitude of knee extension, followed by rapid knee flexion of about 20 degrees until mid-stance. This is again not in agreement with the summarized results published (14), which stated that the first phase of knee flexion occurred during the first 30%, followed by some knee extension until mid-stance. Significant differences were only found in from 40% to 50% stance for knee angular velocity. From the kinematics results, ankle joint appeared to play a more active role then the knee joint in preventive measures to slips when walking on potential slippery walking surface.

Paragraph Number 22 In real construction worksite environments, many other risk factors to slips often occur. It included irregular walking surfaces and obstacles on walking surfaces (4). Moreover, the workers often need to carry various loads in the worksite. This may introduce slipping risk and also the severity of fall. However, the mentioned factors are difficult to simulate and therefore their effects can not easily be investigated. Another important factor is human anticipation (2). The most hazardous situation was believed to be sudden loss of grip due to a sudden drop of available friction in the presence of surface contaminant and without human's anticipation. Suitable signs or notices should be placed in certain area in construction worksite in order to raise the attention of the workers.

Paragraph Number 23 Previous studies were mainly investigating the gait changes in lower extremity (1,2). However, upper extremity kinematics may also reflect the strategy and adaptation evoked by human. In normal level walking, the upper extremity movements are always in opposite to the lower extremity movements to balance the turning moment along either sagittal axis, longitudinal axis or frontal axis. From observation, it appeared that the subjects could also alter the upper extremity pattern in order to achieve gentle foot strike, flat foot landing and finally reduce the required friction from the ground. Moreover, changes in plantar pressure distribution during stance may also reflect adaptation strategy. In obtaining the kinetics data with kinematics data, joint forces and moments could be determined to help understanding human strategy to slip prevention. Future similar studies are suggested to include upper extremity kinematics, normal and shear reaction forces during stance, and plantar pressure distribution information to give a better picture on human preventive measures to slips.

CONCLUSION

Paragraph Number 24 The presence of oil contaminant on wooden walking surface introduced slipping potential in level walking when wearing either safety shoe or cloth shoe. Effective lower extremity changes to prevent slips evolved by human in terms of gait pattern included to increase stance time and stride time, to shorten stride length, to decrease propagation speed and to have a more gentle foot strike in walking. Ankle joint played important strategy in slip prevention. Such strategy included to land on the ground with flat foot, to reduce ankle range of motion, to maintain a stiff ankle joint and to achieve flat-foot landing or plantar-flexed ankle joint during the first 10% stance.

Paragraph Number 25 To prevent occupational slips in construction worksite, workers are advised to walk slowly with shorten stride length and longer foot contact duration. Workers should avoid kicking on the floor during foot strike as this will increase the heel horizontal velocity and the required friction for walking without slips. Moreover, in order to enhance construction worksite safety, the presence of oil contaminant on wooden walkway should be avoided. Suitable signs and notices should be placed in area with frequent occurrence of wooden walking surface and machinery lubricant leakage to attract workers' attention. Workers should also strengthen their ankle joint mobility by proper exercises. Before working in construction site, warm-up exercise of ankle joint movement should be performed.

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Table 1 – Sliding speed, DCOF and slip resistant classification of the sixteen simulated environments in mechanical test

Flooring	Contaminant	Footwear	Sliding speed (m/s)	Dynamic coefficient of friction	Class
Wood	Dry	Safety shoe	.187 (.070)	.796 (.028)	Very slip-resistant
		Cloth shoe	.138 (.062)	.808 (.034)	Very slip-resistant
	Sand	Safety shoe	.364 (.025)	.297 (.023)	Very slip-resistant
		Cloth shoe	.445 (.050)	.286 (.021)	Very slip-resistant
	Water	Safety shoe	.136 (.077)	.736 (.034)	Very slip-resistant
		Cloth shoe	.150 (.092)	1.057 (.056)	Very slip-resistant
	Oil	Safety shoe	.786 (.027)	.197 (.007)	Unsure
		Cloth shoe	.854 (.034)	.107 (.006)	Slippery
Cement	Dry	Safety shoe	.155 (.059)	.668 (.029)	Very slip-resistant
		Cloth shoe	.230 (.106)	.748 (.012)	Very slip-resistant
	Sand	Safety shoe	.365 (.030)	.386 (.025)	Very slip-resistant
		Cloth shoe	.512 (.039)	.368 (.011)	Very slip-resistant
	Water	Safety shoe	.225 (.126)	.594 (.036)	Very slip-resistant
		Cloth shoe	.139 (.088)	.744 (.011)	Very slip-resistant
	Oil	Safety shoe	.461 (.079)	.412 (.023)	Very slip-resistant
		Cloth shoe	.464 (.082)	.291 (.023)	Very slip-resistant

Table 2 – Descriptive statistics, results of ANOVA and Tukey tests of gait pattern parameters

Gait pattern parameters	Mean (SD)			Statistical analysis p-value[a] / Tukey[b]
	Very slip-resistant	Unsure	Slippery	
Stance time (s)	.79 (.06)	.85 (.12)	.92 (.13)	< .01 / (R-U)**, (R-S)**, (U-S)*
Swing time (s)	.42 (.02)	.43 (.03)	.43 (.03)	.01 < p < .05 / not performed
Stride time (s)	1.21 (.08)	1.29 (.14)	1.35 (.15)	< .01 / (R-U)**, (R-S)**
Stride length (m)	1.22 (.08)	1.15 (.09)	1.06 (.10)	< .01 / (R-U)**, (R-S)**, (U-S)**
Heel horizontal velocity at foot strike (ms^{-1})	.52 (.16)	.46 (.17)	.33 (.16)	< .01 / (R-S)**, (U-S)*
Heel vertical velocity at foot strike (ms^{-1})	-.06 (.04)	-.07 (.05)	-.05 (.03)	No significant differences
Heel horizontal acceleration at foot strike (ms^{-2})	-1.54 (.51)	-1.30 (.55)	-1.02 (.49)	< .01 / (R-S)*
Heel vertical acceleration at foot strike (ms^{-2})	1.17 (.50)	1.15 (.61)	.69 (.37)	< .01 / (R-S)**, (U-S)*
Mean propagation speed (ms^{-1})	1.01 (.12)	.91 (.15)	.80 (.15)	< .01 / (R-U)**, (R-S)**, (U-S)*

R – Very slip-resistant, U – Unsure, S – Slippery

[a] ANOVA test of the three classes.

[b] Results of Tukey test showed significant difference between groups – **p < .01, *p < .05.

Table 3 – Descriptive statistics, results of ANOVA and Tukey tests of ankle joint kinematics parameters

Ankle joint kinematics parameters	Mean (SD)			Statistical analysis p-value[a] / Tukey[b]
	Very slip-resistant	Unsure	Slippery	
Included ankle angle, foot strike (°)	111.65 (4.62)	116.69 (5.62)	113.94 (4.05)	< .01 / (R-U)**
Included ankle angle, 10% stance (°)	111.01 (4.47)	115.13 (5.17)	111.68 (4.14)	< .01 / (R-U)**
Included ankle angle, 20% stance (°)	110.53 (4.90)	114.02 (4.68)	108.82 (4.28)	< .01 / (R-U)*, (U-S)*
Included ankle angle, 30% stance (°)	107.28 (5.18)	110.82 (4.56)	104.67 (4.32)	< .01 / (R-U)*, (U-S)**
Included ankle angle, 40% stance (°)	101.76 (5.11)	105.77 (4.51)	99.52 (4.29)	< .01 / (R-U)**, (U-S)**
Included ankle angle, 50% stance (°)	96.37 (5.02)	100.82 (4.85)	94.73 (4.46)	< .01 / (R-U)**, (U-S)**
Ankle angular velocity, foot strike (°/s)	-30.57 (20.30)	-36.93 (14.31)	-26.87 (15.17)	No significant differences
Ankle angular velocity, 10% stance (°/s)	2.80 (27.02)	-8.65 (24.48)	-27.80 (14.16)	< .01 / (R-S)**
Ankle angular velocity, 20% stance (°/s)	-22.63 (18.02)	-23.84 (16.24)	-39.81 (10.34)	< .01 / (R-S)**, (U-S)*
Ankle angular velocity, 30% stance (°/s)	-61.22 (14.46)	-53.24 (5.62)	-55.23 (8.44)	.01 < p < .05 / not performed
Ankle angular velocity, 40% stance (°/s)	-79.34 (16.72)	-66.01 (14.06)	-60.31 (9.55)	< .01 / (R-U)**, (R-S)**
Ankle angular velocity, 50% stance (°/s)	-57.38 (21.85)	-48.50 (20.20)	-44.87 (11.40)	.01 < p < .05 / not performed

R – Very slip-resistant, U – Unsure, S – Slippery

[a] ANOVA test of the three classes.

[b] Results of Tukey test showed significant difference between groups – **p < .01, *p < .05.

Table 4 – Descriptive statistics, results of ANOVA and Tukey tests of knee joint kinematics parameters

Knee joint kinematics parameters	Mean (SD)			Statistical analysis p-value[a] / Tukey[b]
	Very slip-resistant	Unsure	Slippery	
Included knee angle, foot strike (°)	190.95 (5.37)	189.42 (8.41)	190.33 (5.22)	No significant differences
Included knee angle, 10% stance (°)	190.81 (4.95)	189.29 (8.39)	190.30 (5.19)	No significant differences
Included knee angle, 20% stance (°)	192.64 (4.78)	191.15 (8.43)	192.38 (5.13)	No significant differences
Included knee angle, 30% stance (°)	196.50 (4.67)	194.95 (8.41)	196.47 (4.90)	No significant differences
Included knee angle, 40% stance (°)	201.91 (4.60)	200.22 (8.22)	201.97 (4.48)	No significant differences
Included knee angle, 50% stance (°)	207.98 (4.66)	206.10 (7.89)	207.98 (4.01)	No significant differences
Knee angular velocity, foot strike (°/s)	-14.30 (21.73)	-13.73 (17.59)	-12.30 (14.83)	No significant differences
Knee angular velocity, 10% stance (°/s)	10.82 (16.87)	9.93 (13.21)	11.59 (11.16)	No significant differences
Knee angular velocity, 20% stance (°/s)	38.44 (13.30)	35.03 (9.42)	36.32 (9.32)	No significant differences
Knee angular velocity, 30% stance (°/s)	63.70 (11.99)	57.19 (8.05)	57.26 (11.02)	.01 < p < .05 / not performed
Knee angular velocity, 40% stance (°/s)	79.18 (12.89)	70.69 (9.92)	68.83 (14.09)	< .01 / (R-U)*, (R-S)**
Knee angular velocity, 50% stance (°/s)	81.76 (12.86)	72.74 (12.07)	69.51 (15.79)	< .01 / (R-U)*, (R-S)**

R – Very slip-resistant, U – Unsure, S – Slippery

[a] ANOVA test of the three classes.

[b] Results of Tukey test showed significant difference between groups – **p < .01, *p < .05.

Table 5 – Descriptive statistics, results of ANOVA and Tukey tests of foot-floor angle

Knee joint kinematics parameters	Mean (SD)			Statistical analysis p-value[a] / Tukey[b]
	Very slip-resistant	Unsure	Slippery	
Foot-floor angle, foot strike (°)	4.57 (5.08)	.74 (3.70)	2.23 (4.46)	< .01 / (R-U)**
Foot-floor angle, 10% stance (°)	.60 (4.84)	-2.13 (2.77)	-.31 (3.59)	.01 < p < .05
Foot-floor angle, 20% stance (°)	-4.96 (4.22)	-6.94 (1.72)	-3.29 (2.80)	< .01 / (U-S)**
Foot-floor angle, 30% stance (°)	-8.26 (4.18)	-10.14 (1.34)	-5.45 (2.41)	< .01 / (R-S)**, (U-S)**
Foot-floor angle, 40% stance (°)	-9.01 (4.13)	-11.17 (1.30)	-6.48 (2.36)	< .01 / (R-U)*, (R-S)**, (U-S)**
Foot-floor angle, 50% stance (°/s)	-8.55 (4.01)	-10.98 (1.34)	-6.79 (2.41)	< .01 / (R-U)*, (U-S)**

R – Very slip-resistant, U – Unsure, S – Slippery

[a] ANOVA test of the three classes.

[b] Results of Tukey test showed significant difference between groups – **p < .01, *p < .05.

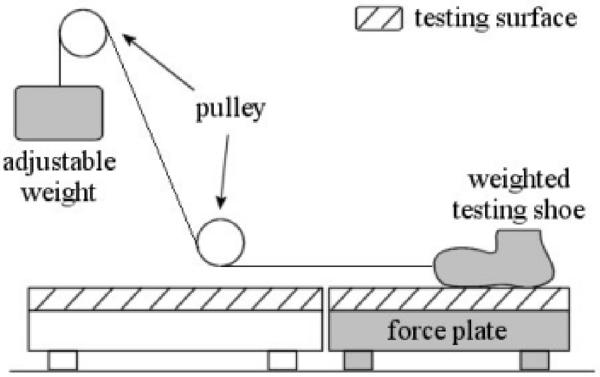

Figure 1 – Pulley system in mechanical slip resistance test

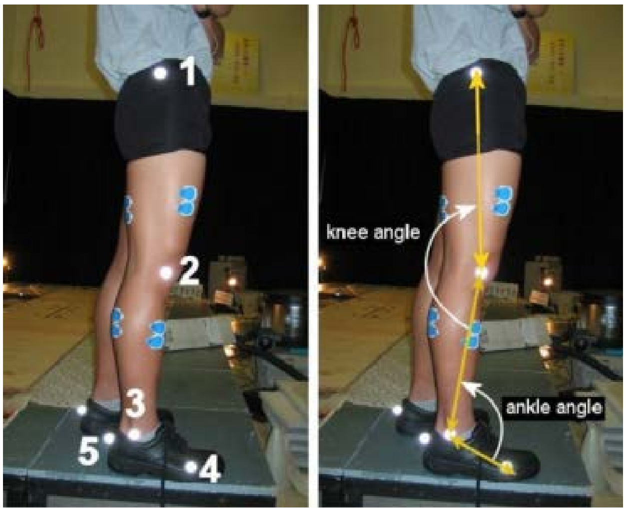

Figure 2 – Marker positions and angle definitions (1 – greater trochanter, 2 – lateral femoral condyle, 3 – lateral malleolus, 4 – fifth metatarsal head, 5 – talus)

Figure 3 – Subject trying the harness to make sure it can arrest him in case of a fall

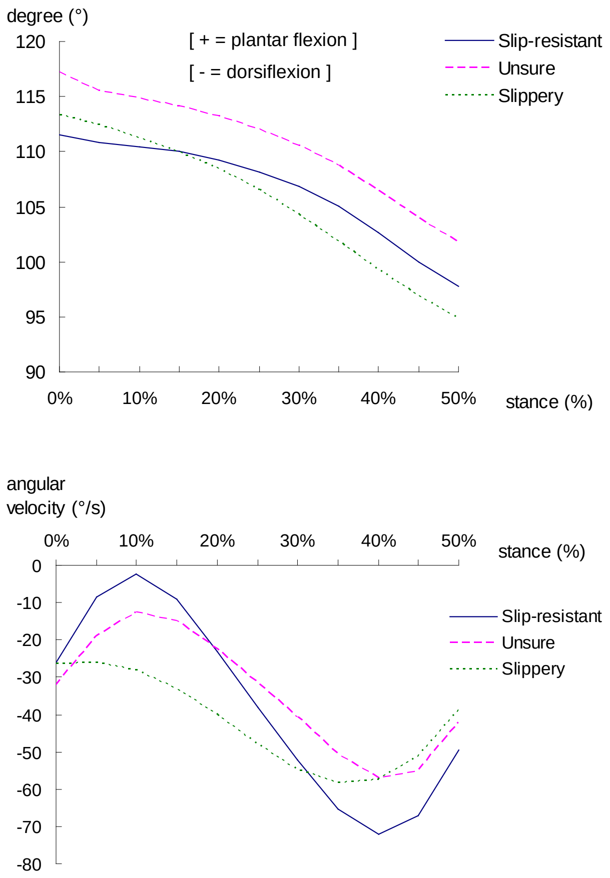

Figure 4 – Included ankle joint profile from foot strike (0% stance) to mid-stance (50% stance)

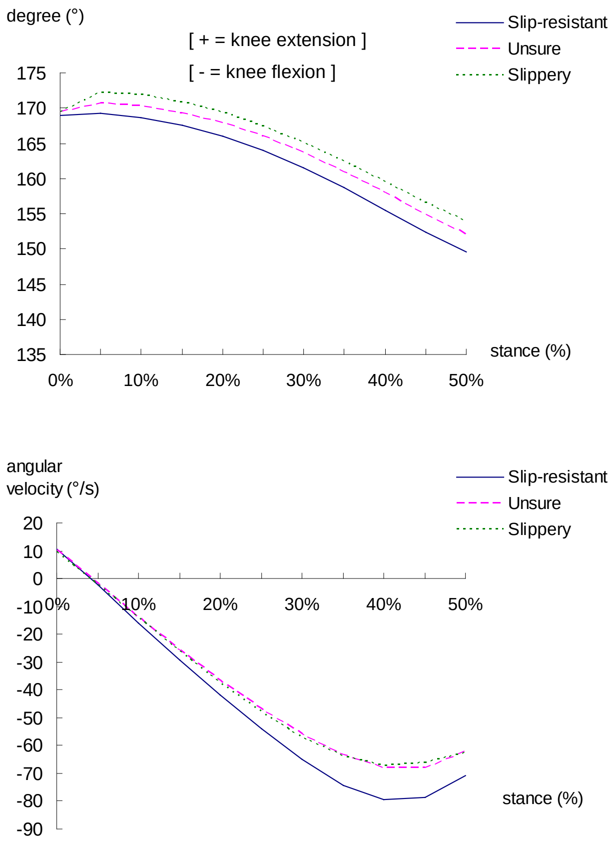

Figure 5 – Included knee joint profile from foot strike (0% stance) to mid-stance (50% stance)

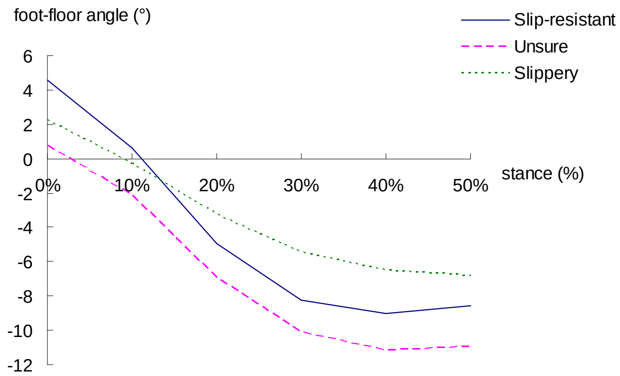

Figure 6 – Foot-floor angle profile from foot strike (0% stance) to mid-stance (50% stance)