SLIP PREVENTION IN WALKING – LOWER EXTREMITY BIOMECHANICS

Daniel Tik-Pui Fong[1], Youlian Hong[2], Jing-Xian Li[3] and Kai-Ming Chan[1]
[1]Department of Orthopaedics and Traumatology,
[2]Department of Sports Science and Physical Education,
The Chinese University of Hong Kong, Hong Kong, China.
[3]School of Human Kinetics, Faculty of Health Science, University of Ottawa, Canada.

This study investigated the human slip prevention strategies when walking on slippery surfaces. Fifteen male subjects performed level walking without slips under sixteen simulated construction site environments. Kinematics, kinetics and electromyography parameters were collected. The slipperiness of the walkway conditions were quantified by the dynamic coefficient of friction (DCOF). Gait changes in slippery condition included prolonged force and pressure exertion in hallux and lateral toes, more ankle plantarflexion moment during 30-50% stance, less knee extension moment during 10-30% stance, higher muscle activity at rectus femoris in late stance, and in gastrocnemius in swing phase. These strategies helped achieving walking without slips by reducing the RCOF from 0.188 to 0.092, which was just lower to the dropped available friction (DCOF=0.107).

KEY WORDS: occupational slips and falls, coefficient of friction, gait adaptation

INTRODUCTION: Slip and falls is the most serious cause of fractures, disability and even deaths. In Hong Kong, statistics of admission to the accident and emergency department of a local hospital reveals that accidental falls is the main cause (41.1%) of hospitalized injuries (OSHCHK, 2000). In occupational settings, construction worksite ranks top (30.1%) in the places of traumatic injury incidents (OSHCHK, 2003). On slippery surfaces, human can adapt by changing their gait. Aetiologically it is to reduce the required friction for gait propagation when the available friction becomes less. In this study, the human slip prevention strategy was investigated by analyzing the gait changes by various simultaneously biomechanics measurements, including kinematics, kinetics and electromyography. The findings will be useful to designing slip prevention program to promote occupational safety.

METHODS: Two floorings, two footwear, and four surface contaminants were selected to simulate sixteen different construction worksite walkway conditions with different slipperiness. The floorings included wood and cement. The footwear included anti-skid safety shoe (EN 345) and cloth sport shoe. The contaminants included dry, sand, water and oil. A mechanical slip-resistance test was conducted to measure the available friction by the value of dynamic coefficient of friction (DCOF), and finally reduced the sixteen conditions into three groups, including “slippery” (DCOF = 0.107), “unsure” (DCOF = 0.197) and “very slip resistant” (DCOF = 0.585) (Fong et al, 2005). Fifteen Chinese male subjects (mean ± S.D.: age: 21.8 ± 1.3 yrs; mass: 64.5 ± 4.6 kg; height: 1.75 ± 0.06 m) participated in a walking test. All subjects were right-legged and with no injury, pain and abnormal gait during the test. Informed consents were obtained. A harness system was employed during the test. It was adjusted for each subject so that it did 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. Each subject performed ten trials on a 5-meter level pathway made by the two types of floorings with the two types of footwear in the sequence of dry, sand, water and oil contaminant conditions. The amounts of the contaminants were 1 L/m^2 for sand, and were 0.5 L/m^2 for water and oil. Before each trial, subject was instructed to avoid slipping and to walk with a self-paced normal speed. Several practice trials were performed prior data collection for the subject to get familiar with the walkway conditions. Trials with slips were discarded as they cannot reflect successful human gait strategies.
Comprehensive biomechanics data were simultaneously collected by various equipments and techniques, and were divided into six categories, including gait pattern, joint kinematics,

ground reaction forces, plantar pressure, internal joint moment and electromyography (Table1). For each data category, multivariate analysis of variance (MANOVA) with repeated measures was conducted to determine significant differences of these parameters between groups with different slipperiness. One-way ANOVA was conducted on each parameter provided that significant effects were shown in MANOVA. For each parameter showing significant difference among groups in ANOVA, pairwise comparisons were conducted. Statistical significance was accepted at the 95% level of confidence.

Table 1 Group classification of the sixteen walkway conditions.

Data category	Parameters collected
Gait pattern	Stance, swing, stride time; stride length; heel horizontal and vertical velocity at foot strike; mean propagation speed
Joint kinematics	Angular displacement and velocity of ankle and knee joint; foot-floor angle
Ground reaction forces	Normalized peak shear and normal forces; time to these forces; peak required coefficient of friction (RCOF); time to peak RCOF
Plantar pressure	Maximum force, peak pressure and their time-integrals in nine districts (medial and lateral heel, medial and lateral mid-foot, metatarsal head I, II, III-V, hallux, lateral toes)
Internal joint moment	Ankle, knee and hip turning moment
Electromyography	Root mean square (RMS) of the EMG signal of tibialis anterior, gastrocnemius, rectus femoris and biceps femoris

RESULTS AND DISCUSSION: The descriptive data of the parameters having a statistical p-value in ANOVA test smaller than .01 and having significant difference shown in Tukey test between "very slip resistant" and "slippery" groups are shown in Table 2. Gait pattern and joint kinematics data were reported in previous study (Fong et al, 2005). MANOVA with repeated measures showed significant effects between groups on all categories of biomechanics parameters (p < .001).

Table 2 descriptive data and statistical analysis results of selected parameters.

Parameters	Mean (SD)			Statistical analysis p-value[a] / Tukey[b]
	Very slip resistant	Unsure	Slippery	
Ground reaction forces parameters				
Normalized peak shear force (N/kg)	1.71 (.37)	1.19 (.24)	.63 (.15)	< .01 / (R-U)**, (R-S)**, (U-S)**
Time of peak shear force (% stance)	13.15 (2.38)	15.23 (3.15)	17.93 (6.41)	< .01 / (R-U)*, (R-S)**, (U-S)*
Normalized peak normal force (N/kg)	11.02 (.72)	10.66 (.52)	9.92 (.76)	< .01 / (R-S)**, (U-S)*
Time of peak normal force (% stance)	17.94 (3.06)	21.63 (6.51)	26.88 (8.09)	< .01 / (R-U)**, (R-S)**, (U-S)**
Peak RCOF	0.188 (.034)	0.136 (.022)	0.092 (.016)	< .01 / (R-U)**, (R-S)**, (U-S)**
Time of peak RCOF (% stance)	10.71 (2.42)	12.59 (2.24)	11.69 (3.02)	< .01 / (R-U)*
Selected plantar pressure parameters (Only showing data showing p<.01 from ANOVA)				
Maximum Force (%BW), hallux	18.1 (5.0)	19.7 (3.5)	26.4 (4.4)	< .01 / (R-S)**
Force-time integrals (%BWs), 1st MH	7.3 (1.9)	8.3 (1.8)	10.4 (2.4)	< .01 / (R-S)**
Force-time integrals (%BWs), hallux	3.6 (1.5)	4.9 (1.6)	9.1 (2.6)	< .01 / (R-S)**, (U-S)**
Force-time integrals (%BWs), lateral toes	2.2 (1.3)	2.6 (.7)	5.4 (1.0)	< .01 / (R-S)**, (U-S)**
Pressure-time integrals (kPas), hallux	50.9 (22.4)	85.0 (26.2)	108.1 (28.7)	< .01 / (R-U)**, (R-S)**
Pressure-time integrals (kPas), lateral toes	21.7 (8.4)	27.5 (7.5)	40.5 (5.0)	< .01 / (R-S)**, (U-S)**
Internal joint moment parameters				
Ankle moment, foot strike (Nm/kg)	-.027 (.037)	-.004 (.014)	-.018 (.028)	No significant differences
Ankle moment, 10% stance (Nm/kg)	.203 (.150)	.184 (.112)	.063 (.143)	No significant differences
Ankle moment, 20% stance (Nm/kg)	.373 (.281)	.321 (.229)	.032 (.216)	< .05 / not performed
Ankle moment, 30% stance (Nm/kg)	.312 (.300)	.235 (.246)	-.107 (.218)	< .01 / (R-S)**, (U-S)*
Ankle moment, 40% stance (Nm/kg)	.138 (.297)	.024 (.220)	-.340 (.219)	< .01 / (R-S)**, (U-S)*
Ankle moment, 50% stance (Nm/kg)	-.017 (.295)	-.158 (.171)	-.555 (.206)	< .01 / (R-S)*, (U-S)*

Knee moment, foot strike (Nm/kg)	-.133 (.149)	-.056 (.052)	-.060 (.047)	No significant differences
Knee moment, 10% stance (Nm/kg)	.409 (.195)	.257 (.079)	.113 (.090)	< .01 / (R-U)*, (R-S)**
Knee moment, 20% stance (Nm/kg)	.851 (.256)	.749 (.163)	.328 (.136)	< .01 / (R-S)**, (U-S)**
Knee moment, 30% stance (Nm/kg)	.873 (.223)	.892 (.218)	.541 (.136)	< .01 / (R-S)**, (U-S)**
Knee moment, 40% stance (Nm/kg)	.861 (.194)	.870 (.215)	.629 (.159)	< .05 / not performed
Knee moment, 50% stance (Nm/kg)	1.031 (.215)	.990 (.140)	.777 (.142)	< .05 / not performed
Hip moment, foot strike (Nm/kg)	-.241 (.360)	-.058 (.103)	-.056 (.086)	No significant differences
Hip moment, 10% stance (Nm/kg)	.148 (.406)	-.056 (.136)	-.139 (.063)	No significant differences
Hip moment, 20% stance (Nm/kg)	.528 (.407)	.446 (.244)	.040 (.159)	< .05 / not performed
Hip moment, 30% stance (Nm/kg)	.513 (.291)	.574 (.160)	.289 (.150)	No significant differences
Hip moment, 40% stance (Nm/kg)	.513 (.240)	.593 (.126)	.435 (.121)	No significant differences
Hip moment, 50% stance (Nm/kg)	.631 (.252)	.695 (.134)	.571 (.120)	No significant differences
Selected electromyography parameters, magnitude normalized % (Only showing data showing p<.01 from ANOVA)				
Gastrocnemius, early swing	.259 (.079)	.340 (.180)	.346 (.197)	< .01 / (R-U)**
Gastrocnemius, late swing	.292 (.099)	.414 (.218)	.496 (.381)	< .01 / (R-U)**, (R-S)**
Rectus femoris, late stance	1.108 (.543)	1.705 (.621)	3.239 (2.102)	< .01 / (R-U)*, (R-S)**, (U-S)**

R – Very slip resistant; U – Unsure; S – Slippery; RCOF – Required coefficient of friction; 1st MH – metatarsal head. a ANOVA test of the three classes.
b Results of Tukey test showed significant difference between groups – **p < .01, *p < .05.

In ground reaction forces, results showed that with increasing slipping potential, there were decreases of normalized peak shear and normal forces from 1.71 to 0.63 N/kg and from 11.02 to 9.92 N/kg respectively. This finally reduced the peak required coefficient of friction (RCOF) to half of its value, from 0.188 to 0.092. The occurrences of these events were also delayed, from about 10-18% stance to about 12-27% stance. In plantar pressure parameters, the significant differences were mainly in hallux, lateral toes and 1st metatarsal head area. The force-time integrals in these three areas out of the total nine areas were significant larger in value (p < .01). The pressure-time integrals in hallux and lateral toes were also longer (p<.01). These showed prolonged force and pressure exertion in slippery condition. Moreover, the maximum force in hallux area was also found to be larger (p < .01). No significant differences were found in the midfoot and rearfoot regions.
In internal joint moment parameters, the main differences occurred from 30-50% stance at ankle, and from 10-30% stance at knee. At ankle the joint moment became negative in value, showing that the ankle joint tended toward plantar flexion during most of the stance time. This may help enhancing flatfoot landing in order to have greater ground reaction forces in normal direction rather than in shear direction to prevent a slip. The knee moments also became smaller in positive value, showing that knee was performing less rapid knee extension. No major differences were found at hip joint at p < .01 level. In electromyography, significant increases in muscle activity were found at gastrocnemius in early and late swing, and also in rectus femoris in late stance. In early stance, which is the critical phase which slip often occurs, there was no significant difference in the muscle activity in the large lower extremity muscles including tibialis anterior, gastrocnemius, rectus femoris and biceps femoris.

CONCLUSION: In this study, with increasing slipping potential, human tended to exert force and pressure in hallux and lateral toes for a prolonged period. The ankle joint was more prone to plantar flexion during 30-50% stance. Knee joint performed significantly less extension during 10-30% stance. In myoelectric analysis, the muscle activities of the four selected lower extremity muscles (tibialis anterior, gastrocnemius, rectus femoris and biceps femoris) did not differ in the early stance phase. However rectus femoris activity was found to be higher in late stance, and gastrocnemius activity was found to be higher in swing phase. All these gait strategies significantly reduced the peak normal force from 11.02 to 9.92 N/kg, and the peak shear force from 1.71 to 0.63 N/kg. Finally the peak required coefficient of friction was reduced to half of its value from 0.188 to 0.092, which was just lower than the available friction in the slippery condition (DCOF = 0.107).

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