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Greater toe grip and gentler heel strike are the strategies to adapt to slippery surface

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Corresponding Author: Dr. Youlian Hong,

Corresponding Author's Institution: The Chinese University of Hong Kong

First Author: Daniel Tik-Pui Fong, MSc

Order of Authors: Daniel Tik-Pui Fong, MSc; De-Wei Mao, PhD; Jing-Xian Li, PhD; Youlian Hong, PhD

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Conflict of interest

Dear Editor of Journal of Biomechanics,

REF: Submission of manuscript titled “Prolonged toe grip and gentler heel strike are the strategies to adapt to slippery surface”.

We declare no financial and personal relationships with other people or organizations that could inappropriately influence this submitted work.

Daniel Tik-Pui FONG,
De-Wei MAO,
Jing-Xian LI,
Youlian HONG

May 3rd, 2007.

Cover Letter

Dear Editor of Journal of Biomechanics,

REF: Submission of manuscript titled “Prolonged toe grip and gentler heel strike are the strategies to adapt to slippery surface”.

We would like to submit the mentioned manuscript as an Original Article to Journal of Biomechanics. Each author has been involved in the design of the study, interpretation of the data, and writing of the manuscript and that each of the authors has read and concurs with the content in the manuscript. The material within has not been and will not be submitted for publication elsewhere except as an abstract. We do not recommend any reviewers and would like to leave the decision to the editors.

Daniel Tik-Pui FONG,
De-Wei MAO,
Jing-Xian LI,
Youlian HONG

May 3rd, 2007.

Article Title	Greater toe grip and gentler heel strike are the strategies to adapt to slippery surface		
Authors	Daniel Tik-Pui FONG ^{1,2} , De-Wei MAO ^{1,3} , Jing-Xian LI ^{1,4} , Youlian HONG ¹		
Affiliations	¹ Department of Sports Science and Physical Education, Faculty of Education, The Chinese University of Hong Kong, Shatin, Hong Kong, China. ² Department of Orthopaedics and Traumatology, Prince of Wales Hospital, Faculty of Medicine, The Chinese University of Hong Kong, Shatin, Hong Kong, China. ³ Shandong Institute of Physical Education and Sports, Jinan, Shandong, China. ⁴ School of Human Kinetics, Faculty of Health Sciences, University of Ottawa, Ontario, Canada.		
Address	Human Movement Laboratory, 101 Kwok Sports Building, The Chinese University of Hong Kong, Shatin, Hong Kong, China		
Correspondence author during review process: Daniel Tik-Pui FONG			
Telephone	(852) 2609 6079	Facsimile	(852) 2603 5781
E-mail	dfong@ort.cuhk.edu.hk / dfong@alumni.cuhk.edu.hk		
Correspondence author if paper is accepted: Youlian HONG			
Telephone	(852) 2609 6082	Facsimile	(852) 2603 5781
E-mail	youlianhong@cuhk.edu.hk		
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1 **ABSTRACT**

2 This study investigated the plantar pressure distribution during gait on wooden surface
3 with different slipperiness in the presence of contaminants. Fifteen Chinese males
4 performed ten walking trials on a 5-meter wooden walkway wearing cloth shoe in
5 four contaminated conditions (dry, sand, water, oil). A pressure insole system was
6 employed to record the plantar pressure data at 50 Hz. Peak pressure and
7 time-normalized pressure-time integral were evaluated in nine regions. In comparing
8 walking on slippery to non-slippery surfaces, results showed a 30% increase of peak
9 pressure beneath the hallux (from 195.6 to 254.1 kPa), with a dramatic 79% increase
10 in the pressure time integral beneath the hallux (from 63.8 to 114.3 kPa) and a 34%
11 increase beneath the lateral toes (from 35.1 to 47.2 kPa). In addition, the peak
12 pressure beneath the medial and lateral heel showed significant 20-24% reductions
13 respectively (from 233.6-253.5 to 204.0-219.0 kPa). These findings suggested that
14 greater toe grip and gentler heel strike are the strategies to adapt to slippery surface.
15 Such strategies plantarflexed the ankle and the metatarsals to achieve a flat foot
16 contact with the ground, especially at heel strike, in order to shift the ground reaction
17 force to a more vertical direction. As the vertical ground reaction force component
18 increased, the available ground friction increased and the floor became less slippery.
19 Therefore, human could walk without slip on slippery surfaces with greater toe grip

20 and gentler heel strike as adaptation strategies.

21

22 **INTRODUCTION**

23 Twenty years ago, slips and falls made people laugh rather than implemented
24 preventive measures (Saari, 1990). This was due to a lack of serious public concern
25 and the common belief that these were just unfortunate or normal accidents (Leamon
26 and Murphy, 1995). In recent decade, public awareness has aroused, as slips and falls
27 caused obvious undesired outcomes, including fracture, disability, financial lost,
28 medical expenditure, and deaths (Courtney and Webster, 1999). Even if a slip does not
29 result in a fall, muscular strain or back pain are often induced from recovery
30 corrective actions (Manning and Shannon, 1981). Redfern et al (2001) suggested that
31 slip events are caused by multiple, interacting environmental and human factors.
32 When the extrinsic environmental factors introduced a potential slippery surface
33 which could be anticipated, i.e., an icy and snowy surface (Gao and Abeysekera,
34 2004), human could evoke changes in intrinsic factors, i.e., gait patterns (Cham and
35 Redfern, 2002), in order to reduce the slip probability. Failure to appropriately change
36 the intrinsic human factors to adapt the extrinsic environmental factors may lead to a
37 slip, and eventually a fall.

38

39 Figure 1 shows a theoretical framework for the understanding of gait adaptation to
40 prevent slip. In walking on level surface, human require certain amount of ground
41 friction to propagate. When the ground friction is enough, ie., when the surface is dry
42 or non-slippery, the available friction is greater than the required friction. Therefore,
43 the ground could accommodate the demand of the human gait, and there is a low
44 chance of slip. When the ground friction is not enough – the available friction is less
45 than the required friction, a slip may occur if one keeps walking without any changes
46 in gait. However, human could adapt by lowering the required friction, or increasing
47 the available friction, in order to walk without slip. Such adaptation could be
48 demonstrated by kinematics, kinetics and myoelectric changes to quantify how human
49 “walk carefully” on slippery surfaces.

50

51 The human foot is the direct contact between the body and the external environment.
52 It supports the body, transmits forces between the body and the ground, adapts to
53 ground surfaces, and acts as a cushion to the remaining body (Chen et al, 1995). It
54 also serves as a system for sensory input to convey information about the magnitude
55 and direction of small strains that occur on the plantar surface, which are crucial to
56 keep balance and avoid falls (Tanaka et al, 1996). The hallux, or the great toe, was
57 suggested to be sensitive to external tactile sense and stimuli. It significantly

58 contributes to the neural feedback to maintain postural stability (Nurse and Nigg,
59 1999). Human can maintain balance by exerting different toe pressure in order to
60 correct for many postural disturbances, i.e., slips and trips, during locomotion (Tanaka
61 et al, 1996). In preventing slips during gait, human also tend to adopt with a gentler
62 heel strike, in order to reduce the collision-forces in the shoe/surface interface during
63 weight acceptance, a factor important for maximizing friction and slip resistance in
64 watery, oily and snowy surfaces (Gronqvist, 1999). Such gentler heel strike was
65 shown by a flat foot landing at heel strike (Fong et al, 2005). The body's center of
66 mass moves forward, so the shoe/floor contact area appears to increase to achieve
67 lower shear forces (Gard and Berggard, 2006). Further kinematics study showed a
68 decrease in horizontal heel velocity, horizontal heel acceleration and vertical heel
69 acceleration at heel strike (Fong et al, 2005). In summary, Gronqvist et al (2001)
70 suggested that the control of foot trajectory to achieve safe ground clearance and
71 gentle heel landing is one critical motor function for safe gait.

72

73 Numerous kinematics studies in the research of slips have been published (Brady et al,
74 2000; Cham and Redfern, 2002; Lockhart et al, 2003; Myung and Smith, 1997). In
75 kinetics, most studies investigated the available friction between shoe and surface by a
76 mechanical test (Aschan et al, 2005; Redfern and Bidanda, 1994), or compared the

77 available and utilized friction during a human gait test (Burnfield et al, 2005; Hanson
78 et al, 1999). To date, no studies reported the plantar pressure kinetics when preventing
79 slips in gait. This study aims to investigate the plantar pressure during gait on wooden
80 surfaces with different slipperiness when contaminated with sand, water and oil.
81 Kinematics, myoelectric and joint moment findings were presented elsewhere (Fong
82 et al, 2005; in press) In this study, it is hypothesized that there are differences in
83 plantar pressure distribution during gait on slippery and non-slippery surfaces, or to be
84 specific, there are gentler heel strike and greater toe grip when walking on slippery
85 surfaces.

86

87 **METHODS**

88 Fifteen Chinese males (age = 21.8 ± 1.3 yr, mass = 64.5 ± 4.6 kg, height = 1.75 ± 0.06
89 m, foot length = 260-265 mm) with no gait abnormalities and with right-leg
90 dominance were recruited for this study. Written informed consent was obtained from
91 all subjects before the study. The university ethics committee approved the study. A
92 harness system was installed to ensure subjects' safety. Each subject wore a pair of
93 cloth shoe of size 42 (length = 265mm) and walked ten times on a 5-meter walking
94 path made of dry wooden surface. The cloth shoe (Fong et al, 2007) was made with a
95 thin layer of cloth upper and a smooth and flexible rubber sole with no compliance to

96 any slip resistance enhancement, thus minimizing any compensation to the surface
97 slipperiness introduced by the contaminants. Moreover, with its thin and flexible
98 rubber sole, it allows the foot to better sense the extrinsic slippery environment. After
99 walking on the dry surface, contaminants were added in the sequence of sand, water
100 and oil (elf 10W40 motor oil). The amounts were about 1 L/m² for sand and 0.5 L/m²
101 for water and oil, which could form a full or almost-full coverage on each plate
102 without spilling out. The testing sequence was not randomized, as to prevent
103 cross-contamination on the testing surface (Hanson et al, 1999), and more importantly,
104 to prevent the gait anticipation effect (Cham and Redfern, 2002).

105

106 The available ground friction of each flooring condition, which was quantified as the
107 dynamic coefficient of friction (DCOF), was evaluated by a mechanical
108 slip-resistance test. A self-designed simple pulley system, which allowed an adjustable
109 horizontal drag force, was used to drag a 11.8-kg-weighted shoe over the wooden
110 testing surface mounted on top of a force plate (Kistler 9281CA, Switzerland) (Fong
111 et al, 2005). Contaminants were added on top of the testing surface. Weights were
112 added to increase the horizontal drag gradually until the shoe slid. The DCOF was
113 obtained by the ratio of shear to normal ground reaction force during the slide. Ten
114 trials were conducted for each flooring condition. According to the measured DCOF

115 and the classification scale suggested by Gronqvist et al (1989), the slipperiness of
116 each condition was classified into very slip resistant, slip resistant, unsure, slippery or
117 very slippery.

118

119 During each walking trial, subjects were instructed to look forward and walk at a
120 self-paced normal speed and avoid slipping. Before each testing condition, each
121 subject was given enough time (about 2 minutes) to practice in order to achieve
122 successful non-slip gait, in order to demonstrate his strategy to adapt to the walkway
123 conditions. One digital video camera (JVC 9600, Japan) with 100 Hz filming rate was
124 used for videotaping the human motion in sagittal plane to detect slips. Reflective
125 markers were attached at the heel counters of the shoe for measuring heel horizontal
126 velocity, and at greater trochanter for measuring the walking speed. Video data were
127 processed and analyzed by a motion analysis system (Ariel Performance Analysis
128 Systems, U.S.). A slip was defined as when the subject required support from the
129 harness as reported by the subject, or when the heel horizontal velocity failed to
130 achieve zero within a 3-cm displacement range (Maynard, 2002) immediately after
131 the foot strike, which was checked by motion analysis. Trials with slips were
132 discarded.

133

134 A pressure insole system (Novel Pedar, Germany) was employed to collect plantar
135 pressure distribution of both feet during each trial. There were 99 sensors in each
136 insole to collect plantar pressure data in kPa at 50Hz. All individual sensors were
137 calibrated with a calibration device (Novel Trublu, Germany). The reliability and
138 validity of this device has been well documented (Kernozeck et al, 1996; Putti et al,
139 2006; Quesada et al, 1997). The pressure distribution data were evaluated in nine
140 regions which were automatically created by the insole system (Novel Automask,
141 Germany), as shown in Figure 2: (1) hallux, (2) lateral toes, (3) 1st metatarsal head, (4)
142 2nd and 3rd metatarsal heads, (5) 4th and 5th metatarsal heads, (6) medial mid-foot, (7)
143 lateral mid-foot, (8) medial heel, and (9) lateral heel. Peak pressure and
144 time-normalized pressure-time integral of each region during a stance period was
145 evaluated. The stance time was determined when the total ground reaction force
146 beneath the foot was over two Newtons, which was automatically identified by the
147 pressure insole system. Since the stance time differed in each trial as a result of
148 different walking speeds, the pressure-time integral was normalized to the stance time.
149 The time-normalized pressure-time integral represents the average amount of pressure
150 exertion or loading within a stance period (Mao et al, 2006). Pressure data from both
151 feet were evaluated together. As walking speed was expected to influence the plantar
152 pressure, analysis of variance (ANOVA) with Tukey post-hoc pairwise comparisons

153 was conducted to investigate any significant difference among the four conditions. If
154 significant difference was found, walking speed would be set as a covariant in the
155 statistical analysis for peak pressure. Since the time-normalized pressure-time integral
156 was already normalized to time, speed would not be set as covariant. Repeated
157 measures one-way analysis of covariance/variance (ANCOVA/ANOVA) was
158 employed to examine the difference in each parameter to see the effects introduced by
159 the surface contaminants. Tukey post-hoc pairwise comparisons were conducted
160 between each pair of contaminant condition when significant differences among were
161 shown in ANCOVA/ANOVA. Significance level was set at $p < 0.05$ level.

162

163 **RESULTS**

164 The four testing conditions had the DCOF value ranging from 0.107 to 1.057 (Table
165 1). The dry and watery conditions were classified as “very slip-resistant” as they had a
166 DCOF value of 0.3 or above. The watery condition had a higher DCOF value (1.057)
167 than the dry condition (0.808). The sand condition was classified as “slip-resistant” as
168 it had a DCOF value of 0.20-0.29. The oily condition was classified as “slippery” as it
169 had a DCOF value lower than 0.14 but higher than 0.05. A total of 600 trials were
170 collected during the human walking test. Eighteen trials (3%) were discarded from the
171 oily condition due to slip occurrence detected by the motion analysis system after data

172 collection.

173

174 The walking speeds of the four conditions are shown in Figure 3. ANOVA with Tukey
175 post-hoc pairwise comparisons showed that the walking speed in trials with oil
176 contaminant was significantly slower than other three trials ($p < 0.05$). Therefore,
177 walking speed was set as a covariate in the statistical analysis for peak pressure.
178 Descriptive data and the results of the ANCOVA/ANOVA and the Tukey post hoc
179 pairwise comparisons are shown in Table 2 and Table 3. On oily surfaces, peak
180 pressures beneath the medial and lateral heel decreased significantly ($p < 0.05$).
181 Significant increase at hallux was also found ($p < 0.05$). Pressure in the mid-foot areas
182 was comparably low and did not differ across all conditions. For time-normalized
183 pressure-time integral, dramatic increases were found beneath the hallux and lateral
184 toes ($p < 0.05$), as illustrated in Figure 4.

185

186 **DISCUSSION**

187 This study investigated the plantar pressure changes during gait on wooden surface
188 with different slipperiness in the presence of sand, water and oil as contaminants. The
189 slipperiness of each condition was represented by the dynamic coefficient of friction
190 (DCOF) measured by a mechanical slip-resistance test. Perkins (1978) suggested that

191 the most critical moment for slips to happen is within 0.05-0.10 second after heel
192 contact, as the ratio of horizontal to vertical ground reaction force during this period is
193 extraordinary high, i.e., the demand of shear ground reaction force could easily
194 exceed the available ground reaction force. During this period of time, the vertical
195 ground reaction force is about 10-20 kg. In this study, a load of 11.8 kg in the shoe
196 was selected for the mechanical slip-resistance test. This represented about 20% body
197 weight of a male adult (about 60kg).

198

199 On wet surface, it was found that the DCOF value was higher than that of dry
200 condition. Although there is a general consensus that wet surface should be slippery,
201 thus, the DCOF value should be lower, there were also previous studies reporting
202 opposite findings. For instance, Manning and Jones (2001) investigated the surface
203 slipperiness between rubber solings with contaminants and found that some rubbers
204 achieved higher coefficient of friction on wet floors. Newton and coworkers (2002)
205 investigated the friction between wrestling shoes and wrestling mats. They found that
206 for old shoe and old mat which has been used over a season, the coefficient of friction
207 was significantly higher in wet (0.76) than in dry (0.60) condition – the wet condition
208 was less slippery. In this test, the shoe and mat surfaces were already smoothed by a
209 one-season usage. The condition was like that of the current study, with smooth

210 wooden surface and shoe with smooth rubber sole. The finding was also in agreement
211 with the result of the current study – the DCOF value in wet condition is higher than
212 that of dry condition. The finding also suggests that the flooring surfaces must be
213 tested by mechanical test, and could not be assumed to be more slippery to a dry
214 condition.

215

216 When walking on non-slippery surfaces (i.e., watery, dry and sandy in this study), the
217 peak pressures were higher beneath the heel and metatarsal regions with values of
218 about 200 kPa. When walking on slippery surfaces (i.e., oily condition in this study),
219 peak pressures at forefoot tended to shift from metatarsal regions to toes, especially to
220 the hallux which showed a 30% increase of peak pressure when compared to the dry
221 conditions (from 195.6 to 254.1 kPa). In addition, there was a dramatic 79% increase
222 in the pressure exertion beneath the hallux (from 63.8 to 114.3 kPa), accompanied
223 with a 34% increase beneath the lateral toes (from 35.1 to 47.2 kPa), as represented by
224 the time-normalized pressure-time integral values. These findings suggest that
225 metatarsal plantarflexion (Shereff et al, 1986) occurred when walking on slippery
226 surfaces, as shown by a slight reduction of peak pressure beneath the metatarsal head
227 regions (from 176.3-206.0 to 162.3-183.6 kPa) and a significant increase of peak
228 pressure beneath the the hallux. Such forefoot motion initiated greater toe grip, which

229 was shown by the increased pressure exertion at the hallux and lateral toes. The
230 results confirmed part of the hypothesis of this study – there is a greater toe grip to
231 adapt to slippery surface in walking.

232

233 The peak pressure beneath the medial and lateral heel showed significant 20-24%
234 reductions in respectively when walking on slippery surfaces (from 233.6-253.5 to
235 204.0-219.0 kPa). This suggested a gentler heel strike was performed, and this finding
236 confirmed the remaining part of the hypothesis of this study – there is a gentler heel
237 strike to adapt to slippery surface in walking. This finding is also accompanied with
238 the slight decrease of the pressure exertion at medial heel (5%, from 80.9 to 76.6 kPa)
239 and lateral heel (6%, from 75.9 to 71.2 kPa), though such reduction was not
240 statistically significant. However, this finding was in agreement of our previous study
241 which showed a flat foot landing at heel strike, and also a gentler heel strike in
242 walking on slippery surfaces as represented by kinematics data (Fong et al, 2005).

243

244 One limitation in this study was the use of safety harness for protecting the subjects
245 from slips and falls. In attempt to minimize this effect, the harness was adjusted for
246 each subject so that it could prevent the subject hitting the ground and at the same
247 time it would not affect the subject's normal gait as perceived and verbally reported

248 by the subject. Walking speed was not controlled in this study and the subjects were
249 instructed to walk at a self-paced normal speed that they would do when they walk on
250 such surfaces with different slipperiness as they could sense, in order to reflect the
251 most realistic slip preventive strategies. The variation of walking speed could be
252 demonstrated by the stance duration. Therefore, the effect of variation of walking
253 speed on the measure parameters was minimized by normalizing the pressure-time
254 integral to the stance duration. Moreover, walking speed was treated as a covariant in
255 the statistical analysis to encounter the effect introduced to the peak pressure
256 measurements.

257

258 The sequence of trials was not randomized, but in order of dry, sand, water and oil.
259 This was to prevent cross-contamination on the testing surface as mentioned by
260 Hanson and coworkers (1999), and more importantly to prevent the gait anticipation
261 effect demonstrated by Cham and Redfern (2002). In their studies, subjects walked on
262 dry surface first, and then on anticipation trial with contaminants, and finally on dry
263 surface again. Even the subjects were told that the final trial was on dry surface and
264 were instructed to walk normally, they still demonstrated significant gait changes as
265 compared with the baseline condition in the first trial on dry surface. Therefore the
266 sequence was assigned in the order in order to minimize such effect. The tests were

267 carried out in a given order with the dry condition done first, followed by the sand
268 condition. The wet and oily surfaces were believed to be more slippery and were put
269 in the last.

270

271 This study suggested that the greater toe grip and gentler heel strike would be the
272 strategy to maintain balance in order to adapt to slippery surface and prevent slip. We
273 postulated that these two adaptations together plantarflexed the ankle and the
274 metatarsals to achieve a flat foot contact with the ground, especially at heel strike
275 (Fong et al, 2005). These strategies shift the ground reaction force to a more vertical
276 direction, which is important in reducing the shear force applying to the ground, and
277 also in gaining greater available ground friction for braking purpose. When the
278 vertical component of ground reaction force is greater, the available ground friction
279 increases as it is a function of the vertical ground reaction force. Therefore, the
280 available ground friction becomes more readily available and the floor becomes less
281 slippery if human could achieve flat foot landing as early as possible after heel strike.

282 In addition, Nurse and Nigg (1999) suggested that the tactile sense of the hallux
283 contributes to the balance control. This is also in agreement that elderly people who
284 practice Tai Chi, which involves lots of hallux pressure exertion, could maintain better
285 balance control and fewer slips and falls (Mao et al, 2006). Therefore, somatosensory

286 training of the activity and the sensation of the hallux could be an intervention to slip
287 prevention. However, footwear may prohibit the sensitivity of the foot to the external
288 environment and stimuli (Nurse and Nigg, 1999), and therefore it is important to
289 include sensory feedback and sensitivity of the foot in shod condition in the future
290 research of slips and falls.

291

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294 Health Council.

295

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Date: 29-10-2007

To: "Youlian Hong" youlianhong@cuhk.edu.hk

From: "Journal of Biomechanics" JBM@elsevier.com

Subject: BM-D-07-00298R1 - Editor Decision

Ref.: Ms. No. BM-D-07-00298R1

Prolonged toe grip and gentler heel strike are the strategies to adapt to slippery surface
Journal of Biomechanics

Dear Dr. Hong,

Thank you for submitting your revised manuscript to the Journal of Biomechanics. Your manuscript has been reviewed by the original referees. I am pleased to inform you that your nice manuscript is acceptable, pending some minor revisions suggested by the reviewers to help clarify your study.

I therefore invite you to submit a revised manuscript, taking account of the reviewers' comments. If you choose to submit a revised manuscript, please provide a list of points of how you have responded to the reviewers' suggestions with the revised manuscript, at your earliest convenience.

To submit a revision, go to <http://ees.elsevier.com/bm/> and log in as an Author. You will see a menu item called Submission Needing Revision. You will find your submission record there. Please update accordingly and submit your revised manuscript."

Please note:

- * Any figures and tables should be included, even if these are unaltered.
- * It is the author's responsibility to ensure that data presented in figures and tables agree with that provided in the text. Please cross check figures, tables and text carefully.
- * Please double-check formatting of your references
- * Please use your word processor to automatically number the lines of your manuscript and provide a word count from the Introduction through the Acknowledgments, including any Appendices.

Thank you again for submitting to the Journal of Biomechanics. I look forward to receiving your revised manuscript.

Yours sincerely,

Farshid Guilak, Ph.D.
Editor-in-Chief

Reviewers' comments:

Reviewer #1: No response

Reviewer #2:

Summary and General Comments:

Overall, the authors did a good job answering the majority of the reviewers' questions. The only issue remained unresolved is that the authors interpreted the increased normalized pressure-time integral (unit: kPa) underneath the hallux and lateral toes area in the slippery oily condition, compared to the dry floor condition, as "prolonged" toe grip. In theory, when the pressure-time integral is normalized (or divided) by the stance time of the gait cycle, the resultant value should indicate the "average pressure" exerted over the investigated area during the whole stance time period. If the authors intended to investigate whether there was a prolonged hallux and toes contact, then the "contact time" of the pressure sensors in these areas should be analyzed. Therefore, it is suggested that the results be interpreted as "stronger toe grip" rather than "prolonged toe grip" while walking on a slippery surface without a fall.

>>> We appreciate this comment, and would like to revise “prolonged toe grip” to “greater toe grip”. The term “stronger toe grip” sounds like a sudden impulse of force exerted by the toe, or a higher ability of toe gripping force. The term “greater toe grip” better refers to a longer and larger exertion of toe grip. Therefore we would like to revise it to be “greater toe grip”. We welcome suggestion from the editor.

Other Specific Suggestions:

Abstract:

Line 13: suggest changing "prolonged toe grip" to "stronger toe grip"

>>> Revised accordingly.

Introduction:

Page 5, lines 12-14 of 1st paragraph: Gronqvist et al (2001) suggested "gentler toe landing" is one of the critical motor adaptations for safe gait while walking on slippery surface. This seems contradictory to the finding of the current study. Please address this issue in discussion.

>>> In Gronqvist's study, some subjects landed with toes and therefore the authors concluded that gentler heel/toe landing is a strategy for safe gait. This is not contradictory to the findings of this study, since the greater toe grip happened after the landing until the next take off. In this study, all subjects landed with heel as instructed, and thus no toe-landing was observed. For simplicity, the toe landing described in Gronqvist's study is omitted in the revised manuscript.

Page 6, line 8: suggest changing "prolonged toe grip" to "stronger toe grip"

>>> Revised accordingly.

Methods:

Page 9, lines 16-17: 2nd paragraph: When the pressure-time integral is normalized (or divided) by the stance time of the gait cycle, the resultant value should indicate the "average pressure", not the total amount of pressure, exerted over the investigated area during the whole stance time period. And, it is important to note that the unit for the resultant value is pressure, not a time measure.

>>> Revised accordingly.

Discussion:

Page 16, 2nd paragraph: Stronger toe grip may be a more appropriate interpretation unless the toe contact time was investigated and longer toe contract time was actually found in slippery condition in this study.

>>> Revised accordingly.

ABSTRACT

This study investigated the plantar pressure distribution during gait on wooden surface with different slipperiness in the presence of contaminants. Fifteen Chinese males performed ten walking trials on a 5-meter wooden walkway wearing cloth shoe in four contaminated conditions (dry, sand, water, oil). A pressure insole system was employed to record the plantar pressure data at 50 Hz. Peak pressure and time-normalized pressure-time integral were evaluated in nine regions. In comparing walking on slippery to non-slippery surfaces, results showed a 30% increase of peak pressure beneath the hallux (from 195.6 to 254.1 kPa), with a dramatic 79% increase in the pressure time integral beneath the hallux (from 63.8 to 114.3 kPa) and a 34% increase beneath the lateral toes (from 35.1 to 47.2 kPa). In addition, the peak pressure beneath the medial and lateral heel showed significant 20-24% reductions respectively (from 233.6-253.5 to 204.0-219.0 kPa). These findings suggested that greater toe grip and gentler heel strike are the strategies to adapt to slippery surface. Such strategies plantarflexed the ankle and the metatarsals to achieve a flat foot contact with the ground, especially at heel strike, in order to shift the ground reaction force to a more vertical direction. As the vertical ground reaction force component increased, the available ground friction increased and the floor became less slippery. Therefore, human could walk without slip on slippery surfaces with greater toe grip

and gentler heel strike as adaptation strategies.

Figure Legend(s)

Figure legends

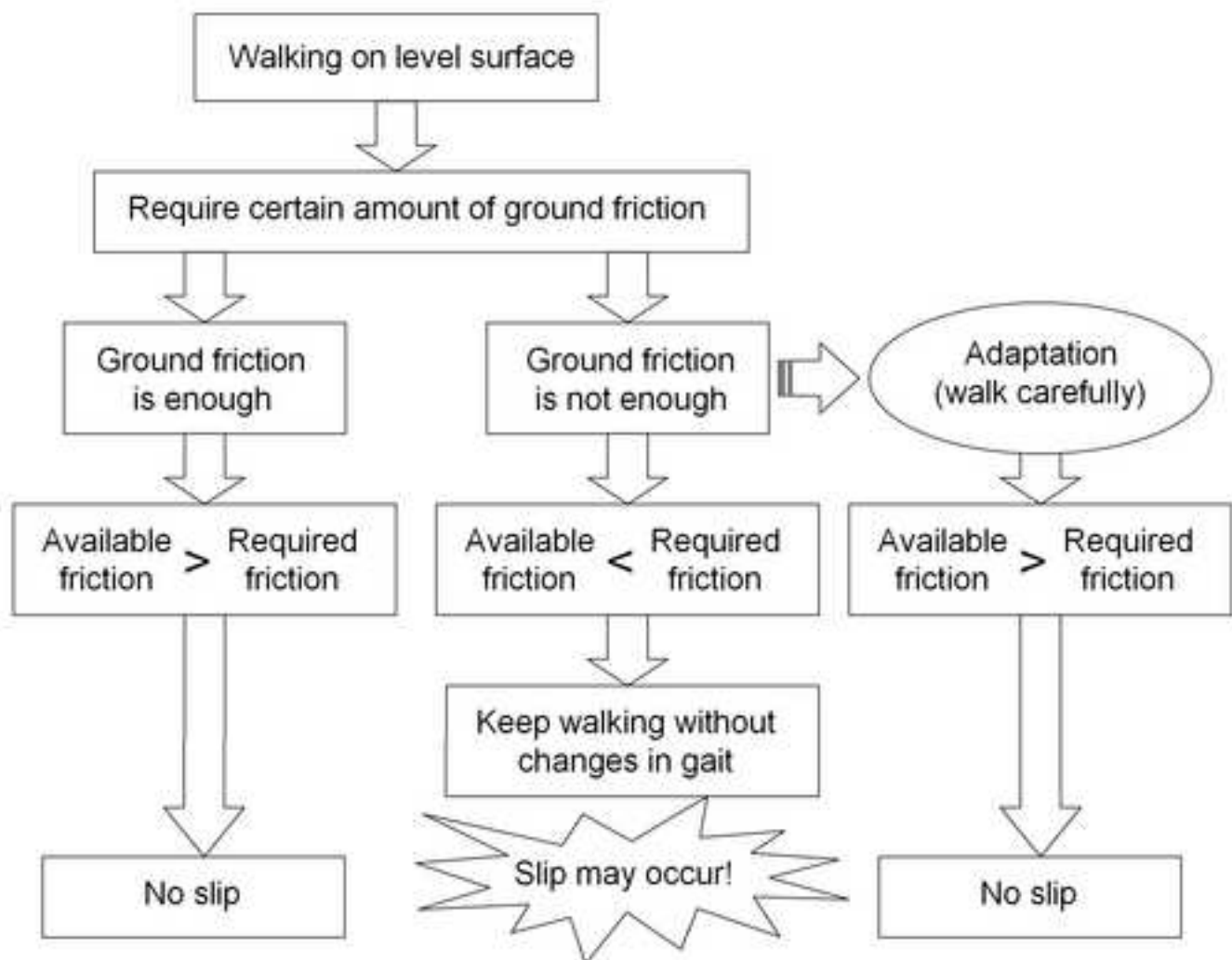
Figure 1 – A theoretical framework for the understanding of gait adaptation to prevent slip.

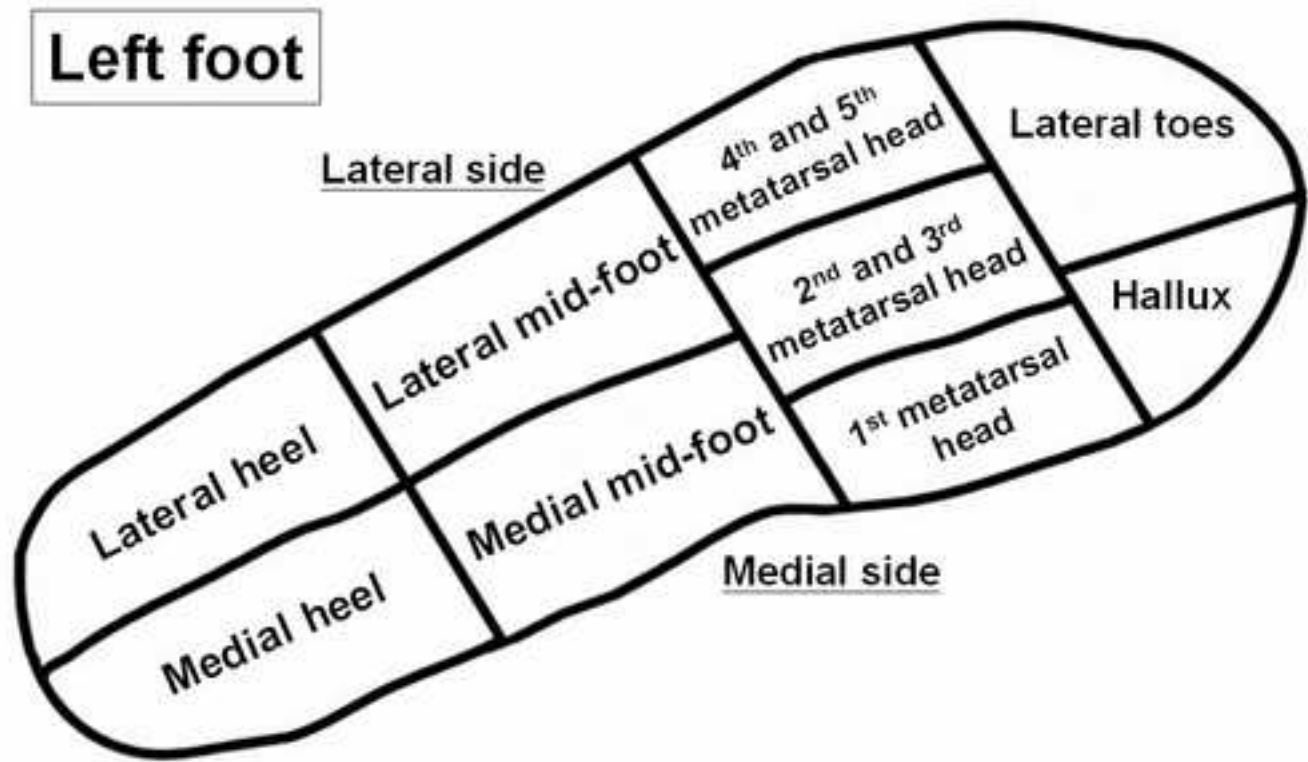
Figure 2 – The nine regions for evaluating the pressure distribution data in this study.

Figure 3 – Walking speed of the trials in the four conditions with different contaminants.

Figure 4– The changes in peak pressure and time-normalized pressure-time integral when walking on slippery conditions (oily condition).

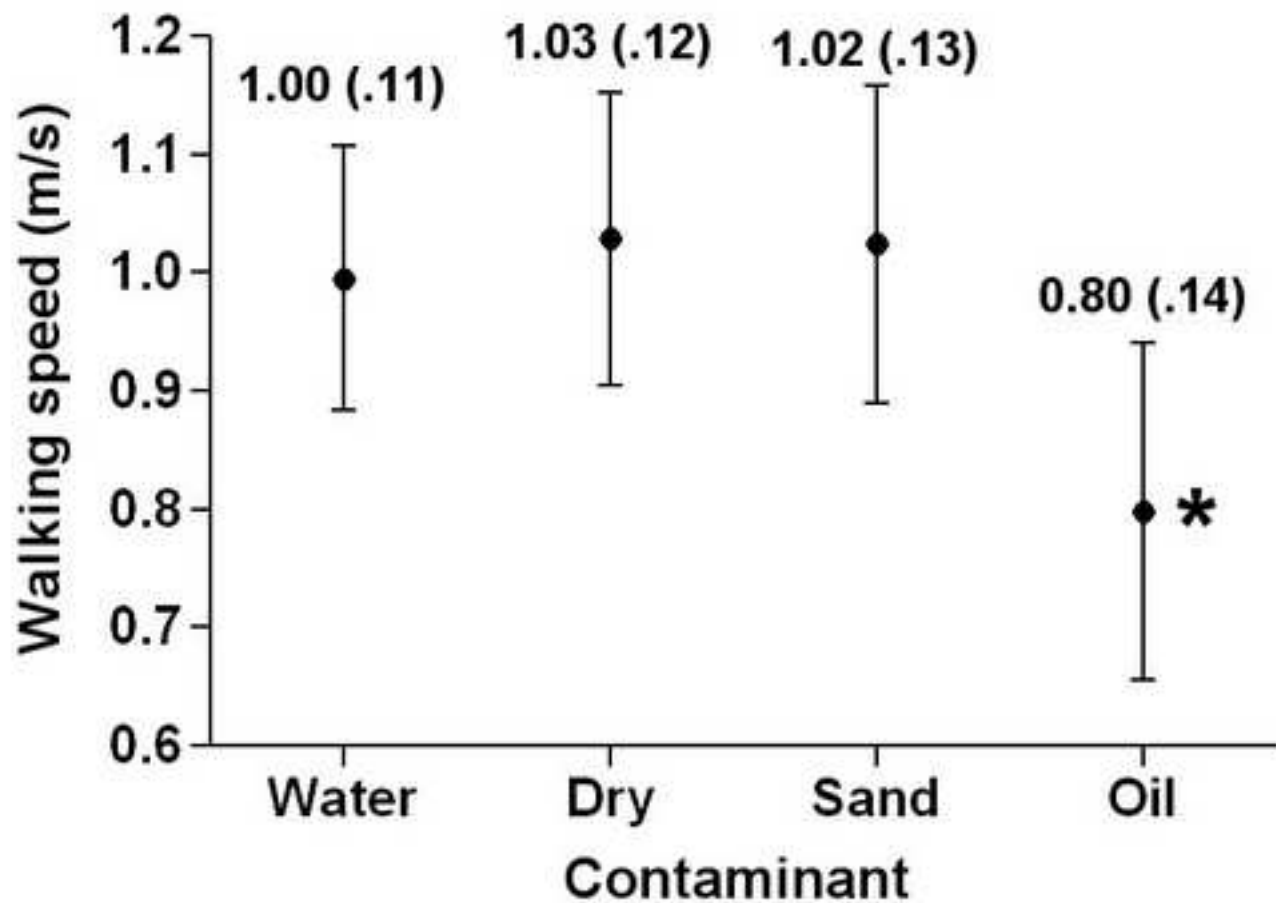
Figure(1)
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Figure(3)

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* = significant difference from all other three contaminants ($p < 0.05$)

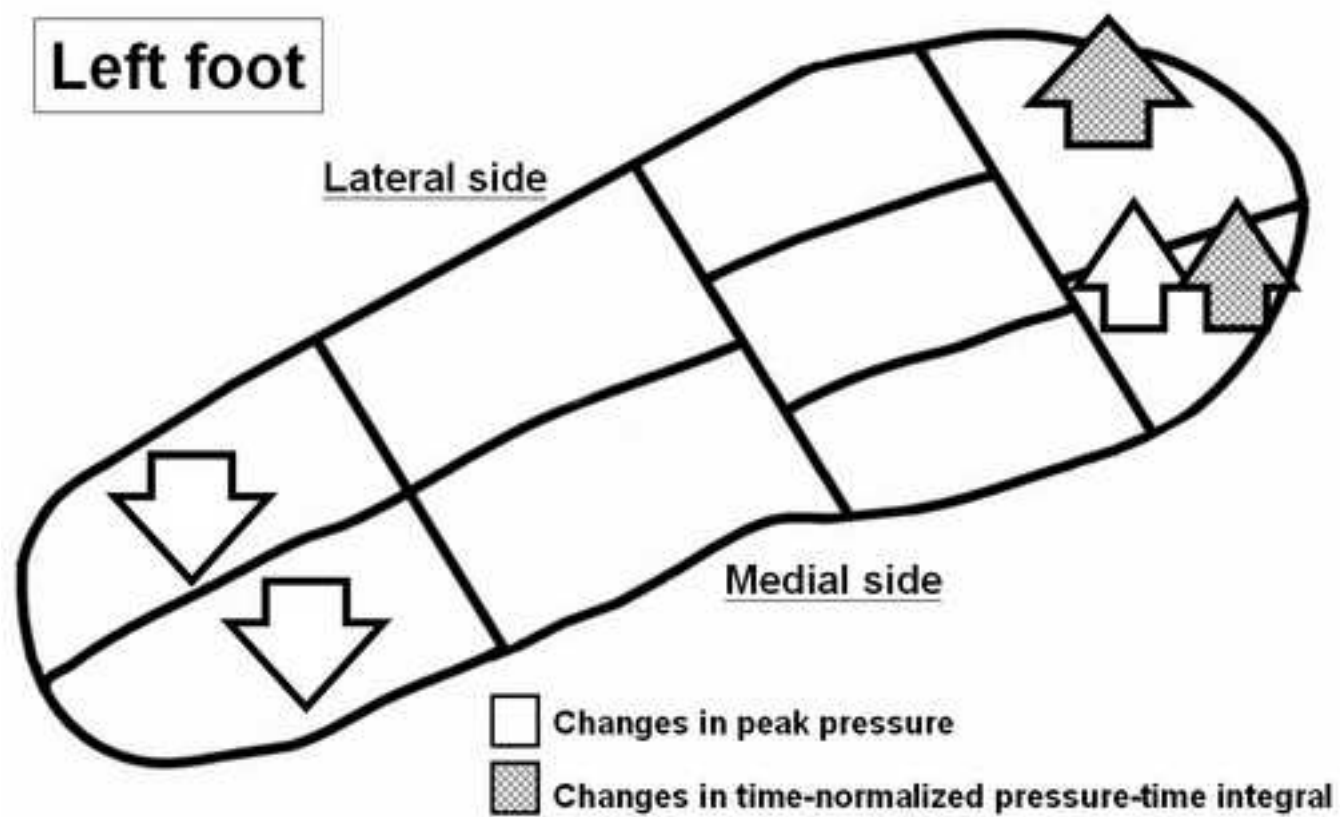


Table 1 – Dynamic coefficient of friction and slip resistant classification of wooden surface with different contaminants in this study

Contaminant	Dynamic coefficient of friction (DCOF)	Slip resistant class (From Gronqvist's scale, 1989)
Water	1.057 (.056)	Very slip-resistant
Dry	.808 (.034)	Very slip-resistant
Sand	.286 (.021)	Slip-resistant
Oil	.107 (.006)	Slippery

Table 2 – Peak pressure (kPa) of the nine regions when walking on different contaminated conditions (in increasing slipperiness order).

	Peak pressure (kPa)				Statistical analysis p-value ^a / Tukey ^b
	Water	Dry	Sand	Oil	
Hallux	179.9 (48.6)	195.6 (36.6)	181.2 (44.5)	254.1 (63.2)	<0.05/(W<O)*, (S<O)*
Lateral toes	110.9 (29.4)	113.3 (23.4)	105.4 (21.5)	120.7 (17.7)	No significant difference
1 st metatarsal head	205.6 (45.6)	176.3 (15.4)	199.1 (41.9)	174.6 (47.7)	No significant difference
2 nd and 3 rd metatarsal heads	228.6 (41.1)	206.0 (24.4)	220.6 (33.3)	183.6 (49.8)	No significant difference
4 th and 5 th metatarsal heads	206.4 (24.7)	194.8 (36.6)	192.9 (26.5)	162.3 (41.4)	No significant difference
Medial mid-foot	35.2 (17.9)	33.3 (18.5)	24.6 (17.5)	29.0 (20.5)	No significant difference
Lateral mid-foot	71.7 (24.1)	77.4 (22.1)	58.1 (25.1)	57.7 (19.4)	No significant difference
Medial heel	275.1 (33.8)	243.2 (13.9)	250.4 (27.4)	219.0 (41.9)	<0.05/(W>D)*, (W>O)*,
Lateral heel	267.6 (38.8)	233.6 (14.0)	246.4 (28.1)	204.0 (45.1)	<0.05/(W>D)*, (W>O)*,
Total	279.2 (35.6)	253.5 (22.6)	258.5 (31.9)	282.1 (43.4)	No significant difference

Contaminants: W – Water, D – Dry, S – Sand, O – Oil

^a ANCOVA test (walking speed as covariant) of the four conditions.

^b Results of Tukey test showed significant difference between groups – *p < .05.

Table 3 – Time-normalized pressure-time integral (kPa) of the nine regions when walking on different contaminated conditions (in increasing slipperiness order).

	Time-normalized pressure-time integral (kPa)				Statistical analysis p-value ^a / Tukey ^b
	Water	Dry	Sand	Oil	
Hallux	48.1 (10.3)	63.8 (15.3)	65.3 (26.1)	114.3 (25.0)	<0.05/(W<O)*, (D<O)*, (S<O)*
Lateral toes	29.1 (8.7)	35.1 (9.1)	31.2 (8.9)	47.2 (8.1)	<0.05/(W<O)*, (D<O)*, (S<O)*
1 st metatarsal head	84.6 (27.6)	81.5 (18.4)	92.6 (25.6)	92.5 (32.6)	No significant difference
2 nd and 3 rd metatarsal heads	100.3 (30.0)	96.5 (20.9)	104.6 (20.8)	97.7 (34.8)	No significant difference
4 th and 5 th metatarsal heads	94.0 (21.7)	93.2 (24.1)	93.1 (13.3)	85.5 (27.4)	No significant difference
Medial mid-foot	10.6 (6.9)	11.2 (8.2)	8.4 (7.2)	8.6 (7.4)	No significant difference
Lateral mid-foot	29.8 (10.0)	35.8 (9.8)	27.3 (12.2)	24.1 (8.7)	No significant difference
Medial heel	88.6 (31.4)	80.9 (20.6)	99.7 (21.7)	76.6 (29.4)	No significant difference
Lateral heel	86.7 (31.4)	75.9 (19.7)	96.4 (21.1)	71.2 (30.0)	No significant difference
Total	167.4 (37.4)	161.4 (25.8)	176.2 (28.2)	180.8 (31.6)	No significant difference

Contaminants: W – Water, D – Dry, S – Sand, O – Oil

^a ANOVA test of the four conditions.

^b Results of Tukey test showed significant difference between groups – *p < .05.