Elsevier Editorial System(tm) for Journal of Biomechanics
Manuscript Draft

Manuscript Number: BM-D-07-00298R2

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

Article Type: Full Length Article (max 3000 words)

Section/Category:

Keywords: Slips and falls, injury prevention, plantar pressure

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

Manuscript Region of Origin:

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.

* Manuscript

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		
Total words	3179	Words in abstract	239
Keywords	Slips and falls, injury prevention, plantar pressure.		

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.

INTRODUCTION

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

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

The human foot is the direct contact between the body and the external environment. It supports the body, transmits forces between the body and the ground, adapts to ground surfaces, and acts as a cushion to the remaining body (Chen et al, 1995). It also serves as a system for sensory input to convey information about the magnitude and direction of small strains that occur on the plantar surface, which are crucial to keep balance and avoid falls (Tanaka et al, 1996). The hallux, or the great toe, was suggested to be sensitive to external tactile sense and stimuli. It significantly contributes to the neural feedback to maintain postural stability (Nurse and Nigg, 1999). Human can maintain balance by exerting different toe pressure in order to correct for many postural disturbances, i.e., slips and trips, during locomotion (Tanaka et al, 1996). In preventing slips during gait, human also tend to adopt with a gentler heel strike, in order to reduce the collision-forces in the shoe/surface interface during weight acceptance, a factor important for maximizing friction and slip resistance in watery, oily and snowy surfaces (Gronqvist, 1999). Such gentler heel strike was shown by a flat foot landing at heel strike (Fong et al, 2005). The body's center of mass moves forward, so the shoe/floor contact area appears to increase to achieve lower shear forces (Gard and Berggard, 2006). Further kinematics study showed a decrease in horizontal heel velocity, horizontal heel acceleration and vertical heel acceleration at heel strike (Fong et al, 2005). In summary, Gronqvist et al (2001) suggested that the control of foot trajectory to achieve safe ground clearance and gentle heel landing is one critical motor function for safe gait.

Numerous kinematics studies in the research of slips have been published (Brady et al, 2000; Cham and Redfern, 2002; Lockhart et al, 2003; Myung and Smith, 1997). In kinetics, most studies investigated the available friction between shoe and surface by a mechanical test (Aschan et al, 2005; Redfern and Bidanda, 1994), or compared the available and utilized friction during a human gait test (Burnfield et al, 2005; Hanson et al, 1999). To date, no studies reported the plantar pressure kinetics when preventing slips in gait. This study aims to investigate the plantar pressure during gait on wooden surfaces with different slipperiness when contaminated with sand, water and oil. Kinematics, myoelectric and joint moment findings were presented elsewhere (Fong et al, 2005; in press) In this study, it is hypothesized that there are differences in plantar pressure distribution during gait on slippery and non-slippery surfaces, or to be specific, there are gentler heel strike and greater toe grip when walking on slippery surfaces.

METHODS

Fifteen Chinese males (age = 21.8 ± 1.3 yr, mass = 64.5 ± 4.6 kg, height = 1.75 ± 0.06 m, foot length = 260-265 mm) with no gait abnormalities and with right-leg dominance were recruited for this study. Written informed consent was obtained from all subjects before the study. The university ethics committee approved the study. A harness system was installed to ensure subjects' safety. Each subject wore a pair of cloth shoe of size 42 (length = 265mm) and walked ten times on a 5-meter walking path made of dry wooden surface. The cloth shoe (Fong et al, 2007) was made with a thin layer of cloth upper and a smooth and flexible rubber sole with no compliance to any slip resistance enhancement, thus minimizing any compensation to the surface slipperiness introduced by the contaminants. Moreover, with its thin and flexible rubber sole, it allows the foot to better sense the extrinsic slippery environment. After walking on the dry surface, contaminants were added in the sequence of sand, water and oil (elf 10W40 motor oil). The amounts were about 1 L/m^2 for sand and 0.5 L/m^2 for water and oil, which could form a full or almost-full coverage on each plate without spilling out. The testing sequence was not randomized, as to prevent cross-contamination on the testing surface (Hanson et al, 1999), and more importantly, to prevent the gait anticipation effect (Cham and Redfern, 2002).

The available ground friction of each flooring condition, which was quantified as the dynamic coefficient of friction (DCOF), was evaluated by a mechanical slip-resistance test. A self-designed simple pulley system, which allowed an adjustable horizontal drag force, was used to drag a 11.8-kg-weighted shoe over the wooden testing surface mounted on top of a force plate (Kistler 9281CA, Switzerland) (Fong et al, 2005). Contaminants were added on top of the testing surface. Weights were added to increase the horizontal drag gradually until the shoe slid. The DCOF was obtained by the ratio of shear to normal ground reaction force during the slide. Ten trials were conducted for each flooring condition. According to the measured DCOF and the classification scale suggested by Gronqvist et al (1989), the slipperiness of each condition was classified into very slip resistant, slip resistant, unsure, slippery or very slippery.

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

A pressure insole system (Novel Pedar, Germany) was employed to collect plantar pressure distribution of both feet during each trial. There were 99 sensors in each insole to collect plantar pressure data in kPa at 50Hz. All individual sensors were calibrated with a calibration device (Novel Trublu, Germany). The reliability and validity of this device has been well documented (Kernozek et al, 1996; Putti et al, 2006; Quesada et al, 1997). The pressure distribution data were evaluated in nine regions which were automatically created by the insole system (Novel Automask, Germany), as shown in Figure 2: (1) hallux, (2) lateral toes, (3) 1st metatarsal head, (4) 2nd and 3rd metatarsal heads, (5) 4th and 5th metatarsal heads, (6) medial mid-foot, (7) lateral mid-foot, (8) medial heel, and (9) lateral heel. Peak pressure and time-normalized pressure-time integral of each region during a stance period was evaluated. The stance time was determined when the total ground reaction force beneath the foot was over two Newtons, which was automatically identified by the pressure insole system. Since the stance time differed in each trial as a result of different walking speeds, the pressure-time integral was normalized to the stance time. The time-normalized pressure-time integral represents the average amount of pressure exertion or loading within a stance period (Mao et al, 2006). Pressure data from both feet were evaluated together. As walking speed was expected to influence the plantar pressure, analysis of variance (ANOVA) with Tukey post-hoc pairwise comparisons was conducted to investigate any significant difference among the four conditions. If significant difference was found, walking speed would be set as a covariant in the statistical analysis for peak pressure. Since the time-normalized pressure-time integral was already normalized to time, speed would not be set as covariant. Repeated measures one-way analysis of covariance/variance (ANCOVA/ANOVA) was employed to examine the difference in each parameter to see the effects introduced by the surface contaminants. Tukey post-hoc pairwise comparisons were conducted between each pair of contaminant condition when significant differences among were shown in ANCOVA/ANOVA. Significance level was set at $p < 0.05$ level.

RESULTS

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

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

DISCUSSION

This study investigated the plantar pressure changes during gait on wooden surface with different slipperiness in the presence of sand, water and oil as contaminants. The slipperiness of each condition was represented by the dynamic coefficient of friction (DCOF) measured by a mechanical slip-resistance test. Perkins (1978) suggested that the most critical moment for slips to happen is within 0.05-0.10 second after heel contact, as the ratio of horizontal to vertical ground reaction force during this period is extraordinary high, i.e., the demand of shear ground reaction force could easily exceed the available ground reaction force. During this period of time, the vertical ground reaction force is about 10-20 kg. In this study, a load of 11.8 kg in the shoe was selected for the mechanical slip-resistance test. This represented about 20% body weight of a male adult (about 60kg).

On wet surface, it was found that the DCOF value was higher than that of dry condition. Although there is a general consensus that wet surface should be slippery, thus, the DCOF value should be lower, there were also previous studies reporting opposite findings. For instance, Manning and Jones (2001) investigated the surface slipperiness between rubber solings with contaminants and found that some rubbers achieved higher coefficient of friction on wet floors. Newton and coworkers (2002) investigated the friction between wrestling shoes and wrestling mats. They found that for old shoe and old mat which has been used over a season, the coefficient of friction was significantly higher in wet (0.76) than in dry (0.60) condition – the wet condition was less slippery. In this test, the shoe and mat surfaces were already smoothened by a one-season usage. The condition was like that of the current study, with smooth wooden surface and shoe with smooth rubber sole. The finding was also in agreement with the result of the current study – the DCOF value in wet condition is higher than that of dry condition. The finding also suggests that the flooring surfaces must be tested by mechanical test, and could not be assumed to be more slippery to a dry condition.

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

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

One limitation in this study was the use of safety harness for protecting the subjects from slips and falls. In attempt to minimize this effect, the harness was adjusted for each subject so that it could prevent the subject hitting the ground and at the same time it would not affect the subject's normal gait as perceived and verbally reported by the subject. Walking speed was not controlled in this study and the subjects were instructed to walk at a self-paced normal speed that they would do when they walk on such surfaces with different slipperiness as they could sense, in order to reflect the most realistic slip preventive strategies. The variation of walking speed could be demonstrated by the stance duration. Therefore, the effect of variation of walking speed on the measure parameters was minimized by normalizing the pressure-time integral to the stance duration. Moreover, walking speed was treated as a covariant in the statistical analysis to encounter the effect introduced to the peak pressure measurements.

The sequence of trials was not randomized, but in order of dry, sand, water and oil. This was to prevent cross-contamination on the testing surface as mentioned by Hanson and coworkers (1999), and more importantly to prevent the gait anticipation effect demonstrated by Cham and Redfern (2002). In their studies, subjects walked on dry surface first, and then on anticipation trial with contaminants, and finally on dry surface again. Even the subjects were told that the final trial was on dry surface and were instructed to walk normally, they still demonstrated significant gait changes as compared with the baseline condition in the first trial on dry surface. Therefore the sequence was assigned in the order in order to minimize such effect. The tests were carried out in a given order with the dry condition done first, followed by the sand condition. The wet and oily surfaces were believed to be more slippery and were put in the last.

This study suggested that the greater toe grip and gentler heel strike would be the strategy to maintain balance in order to adapt to slippery surface and prevent slip. We postulated that these two adaptations together plantarflexed the ankle and the metatarsals to achieve a flat foot contact with the ground, especially at heel strike (Fong et al, 2005). These strategies shift the ground reaction force to a more vertical direction, which is important in reducing the shear force applying to the ground, and also in gaining greater available ground friction for braking purpose. When the vertical component of ground reaction force is greater, the available ground friction increases as it is a function of the vertical ground reaction force. Therefore, the available ground friction becomes more readily available and the floor becomes less slippery if human could achieve flat foot landing as early as possible after heel strike. In addition, Nurse and Nigg (1999) suggested that the tactile sense of the hallux contributes to the balance control. This is also in agreement that elderly people who practice Tai Chi, which involves lots of hallux pressure exertion, could maintain better balance control and fewer slips and falls (Mao et al, 2006). Therefore, somatosensory training of the activity and the sensation of the hallux could be an intervention to slip prevention. However, footwear may prohibit the sensitivity of the foot to the external environment and stimuli (Nurse and Nigg, 1999), and therefore it is important to include sensory feedback and sensitivity of the foot in shod condition in the future research of slips and falls.

ACKNOWLEDGEMENT

This study was financially supported by the Hong Kong Occupational Safety and Health Council.

REFERENCES

Aschan, C., Hirvonen, M., Mannelin, T., Rajamaki, E., 2005. Development and validation of a novel portable slip simulator. Applied Ergonomics 36, 585-593.

Brady, R.A., Pavol, M.J., Owings, T.M., Grabiner, M.D., 2000. Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking. Journal of Biomechanics 33, 803-808.

Burnfield, J.M., Tsai, Y.J., Powers, C.M., 2005. Comparison of utilized coefficient of friction during different walking tasks in persons with and without a disability. Gait and Posture 22, 82-88.

Cham, R., Redfern, M.S., 2002. Changes in gait when anticipating slippery floors. Gait and Posture 15, 159-171.

Chen, H., Nigg, B.M., Hulliger, M., de Koning, J., 1995. Influence of sensory input on plantar pressure distribution. Clinical Biomechanics 10, 271-274.

Courtney, T.K., Webster, B.S., 1999. Disabling occupational morbidity in the United States. An alternative way of seeing the Bureau of Labor statistics' data. Journal of Occupational Environmental Medicine 41, 60-69.

Fong, D.T.P., Hong, Y., Li, J.X., 2005. Lower-extremity gait kinematics on slippery surfaces in construction worksites. Medicine and Science in Sports and Exercise 37, 447-454.

Fong, D.T.P., Hong, Y., Li, J.X., 2007. Cushioning and lateral stability functions of cloth sport shoes. Sports Biomechanics 6, 407-417.

Fong, D.T.P., Hong, Y., Li, J.X., in press. Lower extremity preventive measures for slips – joint moments and myoelectric analysis. Ergonomics.

Gao, C., Abeysekera, J., 2004. A systems perspective of slip and fall accidents on icy and snowy surfaces. Ergonomics 47, 573-598.

Gard, G., Berggard, G., 2006. Assessment of anti-slip devices from healthy individuals in different ages walking on slippery surfaces. Applied Ergonomics 37, 177-186.

Gronqvist, R, 1999. Slips and falls. In: Kumar, S. (Ed.), Biomechanics in Ergonomics. Taylor & Francis, London, pp. 351-375.

Gronqvist, R., Chang, W.R., Courtney, T.K., Leamon, T.B., Redfern, M.S., Strandberg, L., 2001. Measurement of slipperiness: Fundamental concepts and definitions. Ergonomics 44, 1102-1117.

Gronqvist, R., Roine, J., Jarvinen, E., Korhonen, E., 1989. An apparatus and a method for determining the slip resistance of shoes and floors by simulation of human foot motions. Ergonomics 32, 979-995.

Hanson, J.P., Redfern, M.S., Mazumdar, M., 1999. Predicting slips and falls considering required and available friction. Ergonomics 42, 1619-1633.

Kernozek, T.W., LaMott, E.E., Dancisak, M.J., 1996. Reliability of an in-shoe pressure measurement system during treadmill walking. Foot and Ankle International 17, 204-209.

Leamon, T.B., Murphy, P.L., 1995. Occupational slips and falls: More than a trivial problem. Ergonomics 38, 487-498.

Lockhart, T.E., Woldstad, J.C., Smith, J.L., 2003. Effects of age-related gait changes on the biomechanics of slips and falls. Ergonomics 46, 1136-1160.

Manning, D.P., Shannon, H.S., 1981. Slipping accidents causing low-back pain in a gearbox factory. Spine 6, 70-72.

Manning, D.P., Jones, C., 2001. The effect of roughness, floor polish, water, oil and ice on underfoot friction: current safety footwear solings are less slip resistant than microcellular polyurethane. Applied Ergonomics 32, 185-196.

Mao, D.W., Li, J.X., Hong, Y., 2006. Plantar pressure distribution during tai chi exercise. Archives of Physical Medicine and Rehabilitation 87, 814-820.

Maynard, W.S., 2002. Tribology: Preventing slips and falls in the workplace. Occupational Health and Safety 71, 134-140.

Myung, R., Smith, J.L., 1997. The effect of load carrying and floor contaminants on slip and fall parameters. Ergonomics 40, 235-246.

Newton, R., Doan, B., Meese, M., Conroy, B., Black, K., Sebstianelli, W., Kramer, W., 2002. Interaction of wrestling shoe and competition surface: effects on coefficient of friction with implications for injury. Sports Biomechanics 1, 157-166.

Nurse, M.A., Nigg, B.M., 1999. Quantifying a relationship between tactile and vibration sensitivity of the human foot with plantar pressure distributions during gait. Clinical Biomechanics 14, 667-672.

Perkins, P.J., 1978. Measurement of slip between the shoe and ground during walking.

In: Anderson, C., Senne, H. (Eds.), Walkway Surfaces: Measurement of Slip Resistance, ASTM Special-Technical-Publication 649. American Society for Testing and Materials, Philadelphia, pp. 71-87.

Putti, A.B., Arnold, G.P., Cochrane, L., Abboud, R.J., 2007. The Pedar in-shoe system: Repeatability and normal pressure values. Gait and Posture 25, 401-405.

Quesada, P., Rash, G., Jarboe, N., 1997. Assessment of Pedar and F-Scan revisited. Clinical Biomechanics 12, S15.

Redfern, M.S., Bidanda, B, 1994. Slip resistance of the shoe floor interface under biomechanically-relevant conditions. Ergonomics 37, 511-524.

Redfern, M.S., Cham, R., Gielo-Perczak, K., Gronqvist, R., Hirvonen, M., Lanshammar, H., Marpet, M., Pai, C.Y., Powers, C., 2001. Biomechanics of slips. Ergonomics 44, 1138-1166.

Saari, J., 1990. On strategies and methods in company safety work: From informational to motivational strategies. Journal of Occupational Accidents 12, 107-117.

Shereff, M.J., Bejjani, F.J., Kummer, F.J., 1985. Kinematics of the first metatarsophalangeal joint. Journal of Bone and Joint Surgery – American Volume 68, 392-398.

Tanaka, T., Noriyasu, S., Ino, S., Ifukube, T., Nakata, M., 1996. Objective method to determine the contribution of the great toe to standing balance and preliminary observations of age-related effects. IEEE Transactions on Rehabilitation Engineering 4, 84-90.

* **Revision Notes**

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 legends

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

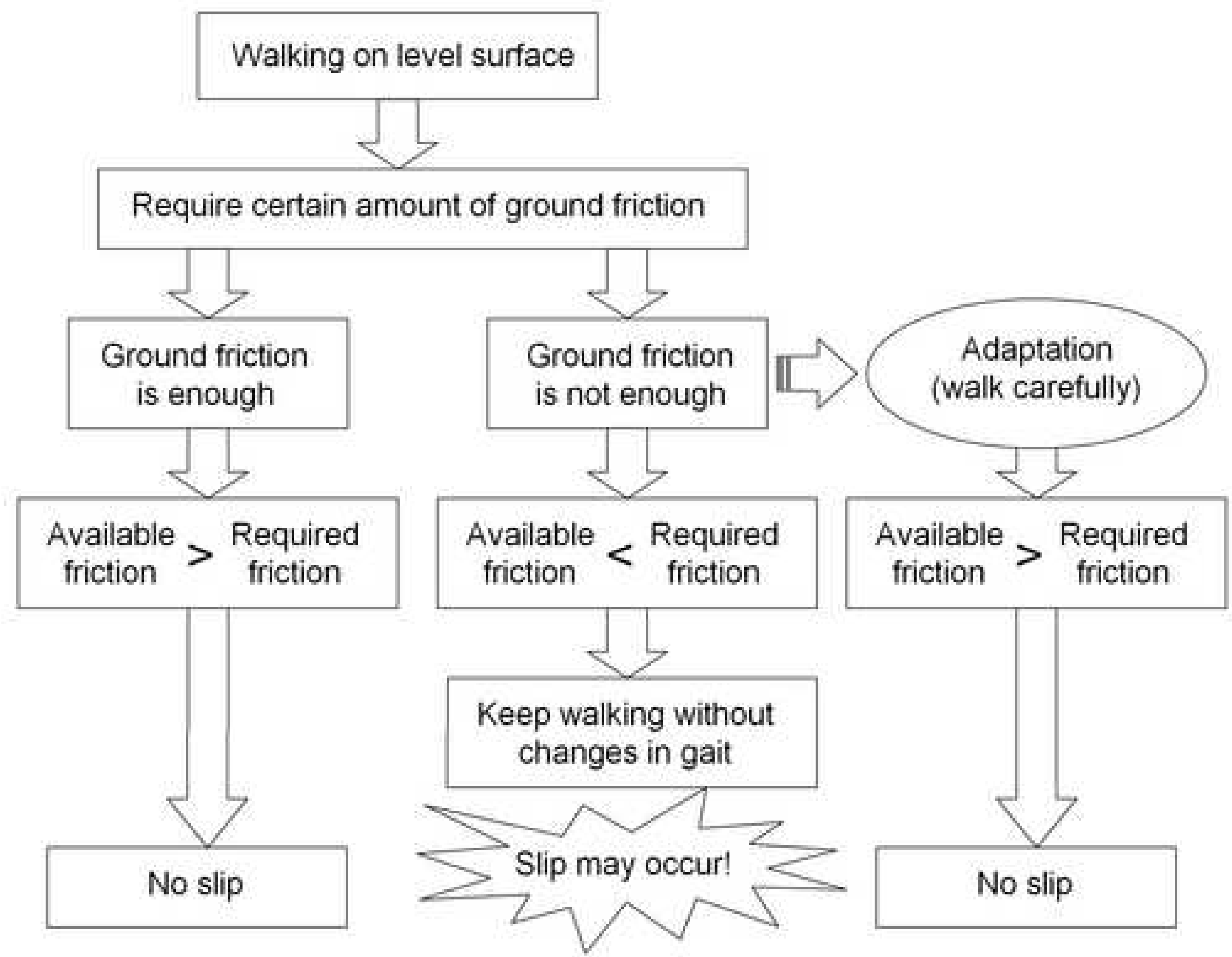
Figure 2 – The nine regions for evaluating the pressure distribution data in this study.

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).

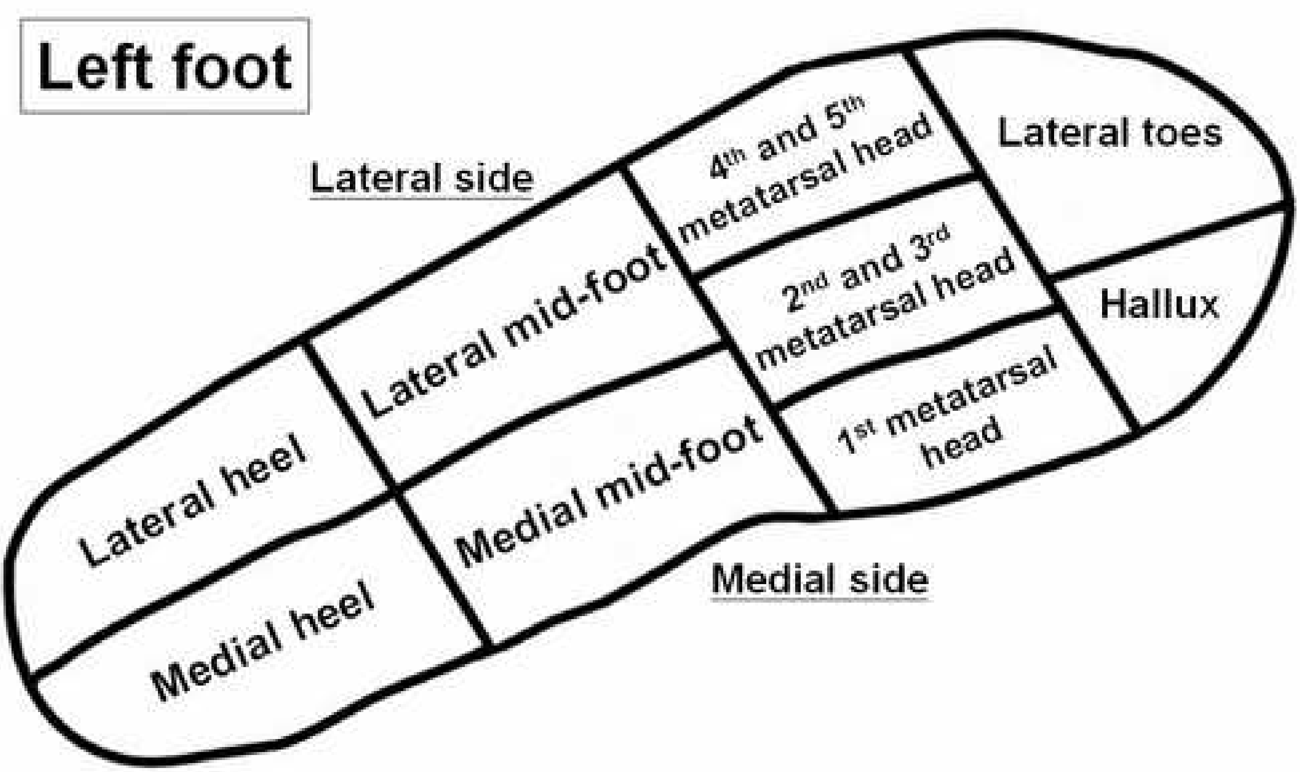
Figure(1)

Click here to download high resolution image

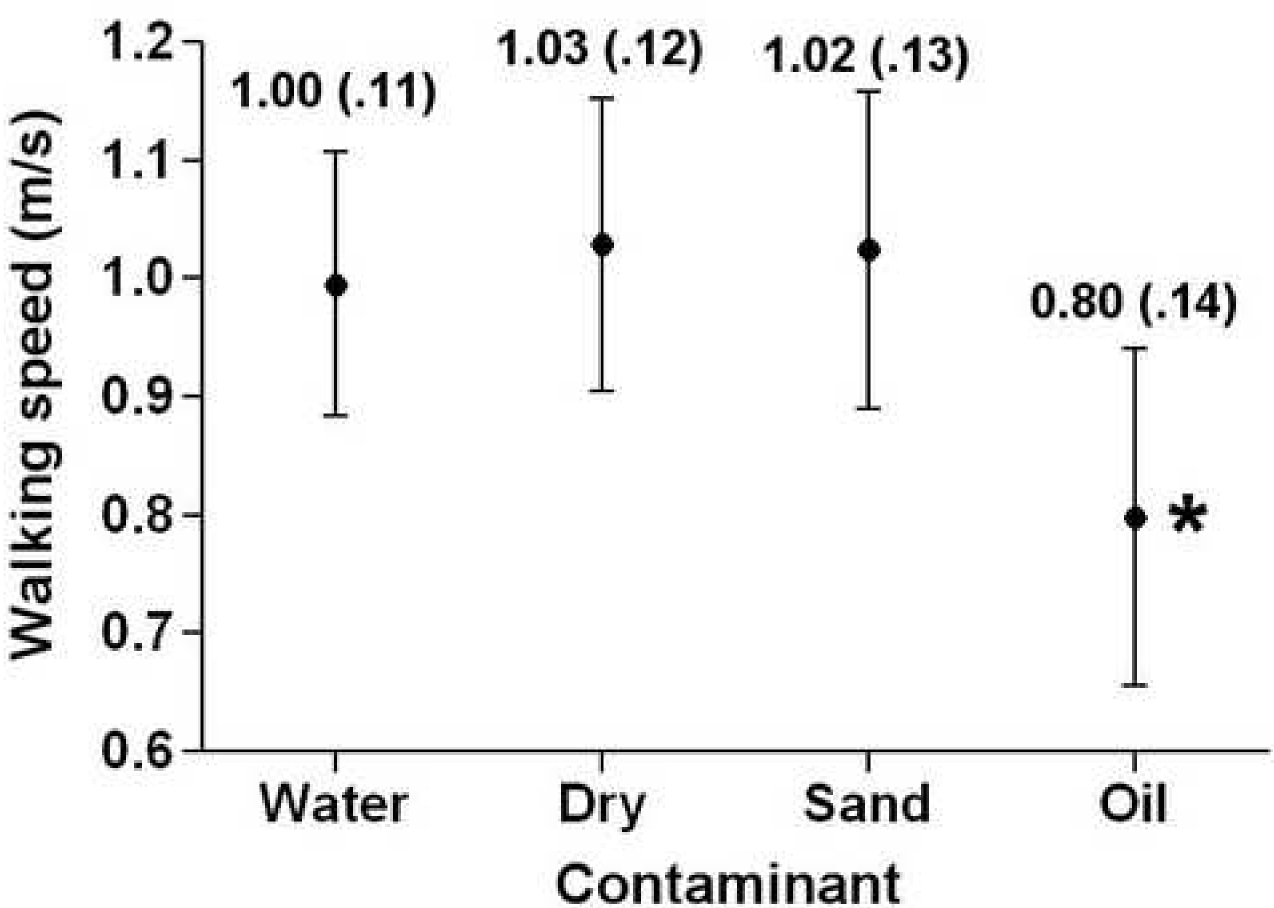


Figure(2)

Click here to download high resolution image



Figure(3)
Click here to download high resolution image



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

Figure(4)
Click here to download high resolution image

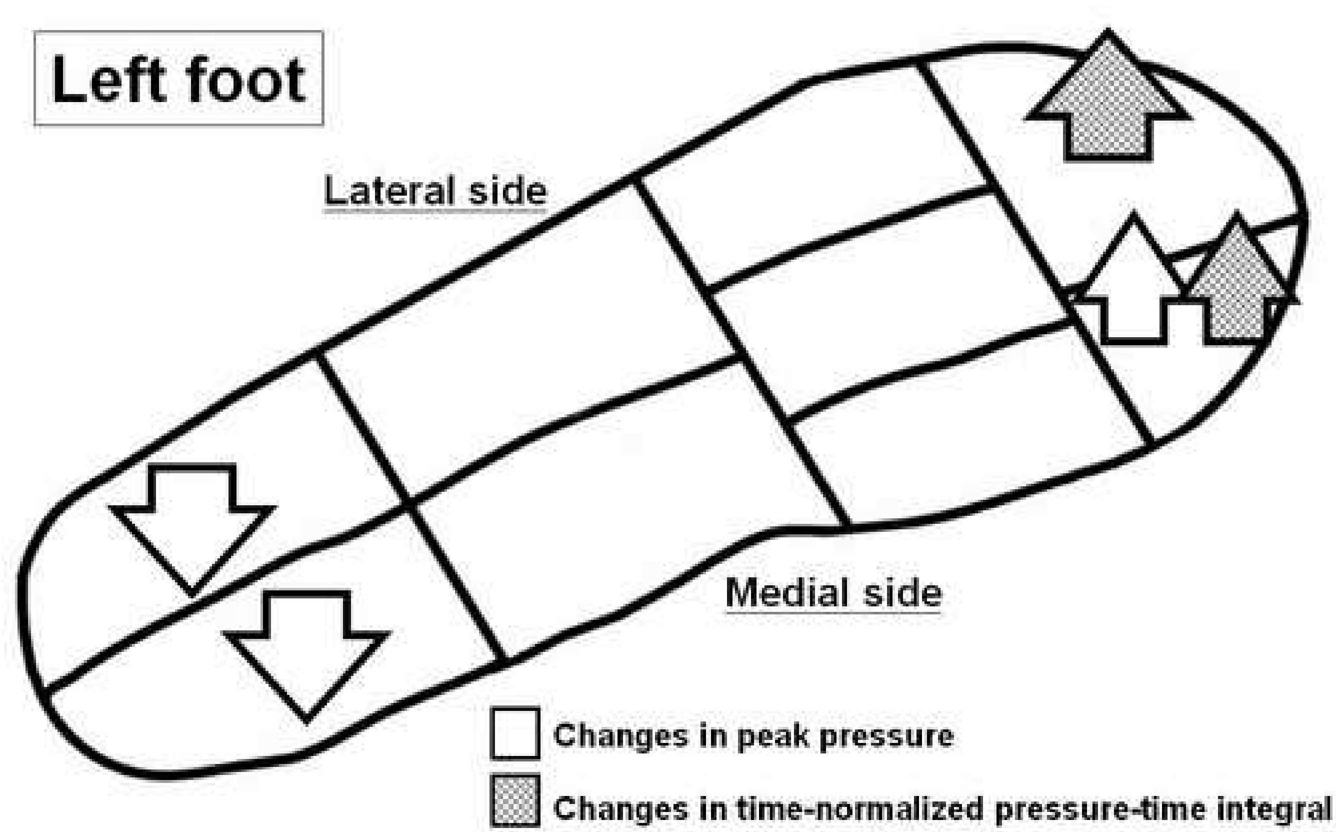


Table 1 – Dynamic coefficient of friction and slip resistant classification of wooden surface with different contaminants in this study

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)				
	Water	Dry	Sand	Oil	Statistical analysis p-value[a] / Tukey[b]
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)				
	Water	Dry	Sand	Oil	Statistical analysis p-value[a] / Tukey[b]
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)*
1st metatarsal head	84.6 (27.6)	81.5 (18.4)	92.6 (25.6)	92.5 (32.6)	No significant difference
2nd and 3rd metatarsal heads	100.3 (30.0)	96.5 (20.9)	104.6 (20.8)	97.7 (34.8)	No significant difference
4th and 5th 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 – *$p < .05$.