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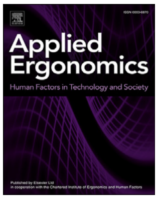

Gait adaptation on surfaces with different degrees of slipperiness

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ABSTRACT

Gait adaptation to employ different ways to avoid a potential slip is needed to continue walking safely on a new surface, especially when transitioning to a slippery surface. In this experiment, participants walked back and forth five times (trials) on surfaces with different degrees of slipperiness. The results show that trial 1 was significantly different from other trials for most of the dependent variables, especially for the low and high friction conditions. Kinematics on high and medium friction surfaces were very similar, but more adjustments were needed for low friction surfaces. The data for the first trial reflect gait after walking for 2.4 m on the walkway, not the first step onto the walkway. The current data show that gait adaptation continued beyond the first trial. Since participants in this experiment were aware of the floor conditions, the results could have important safety implications that user awareness alone might be insufficient for safe floor designs.

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1. Introduction

Data from the Liberty Mutual Workplace Safety Index (Liberty Mutual Research Institute for Safety, 2016) show that the costs for disabling workplace injuries in 2013 due to falls on the same level in the U.S. were estimated to be approximately 10.17 billion US dollars or 16.4% of the total cost burden. For falls on the same level, slippery floors, mostly caused by contaminants, are a critical factor (Chang et al., 2001b). Bell et al. (2008) identified liquid contamination as the most common cause (24%) of slip, trip and fall incidents for healthcare workers. Falls on the same level continue to be a serious occupational injury problem.

Generally, there are two scenarios for quantifying biomechanical responses to slippery areas. As summarized by Redfern et al. (2001), one scenario is to measure human responses to unexpected slippery conditions. This scenario simulates situations where pedestrians unknowingly step onto a slippery area. Heel contact angle, and heel velocity and acceleration in horizontal and vertical directions at the instant of heel contact are typical output measures to characterize biomechanical responses (Redfern et al., 2001). The second scenario is to investigate human adaptations to known slippery surfaces by altering gait to avoid a slip. Quite often, pedestrians may encounter a transition in floor conditions such as from one floor surface to another or the same floor surface with different surface conditions. Multiple sensing mechanisms potentially could be used in human locomotion, so an iterative process is needed to coordinate body responses to avoid slipping and, ultimately, falling, when transitioning to a slippery area. During this gait adaptation period, pedestrians are exploring different ways to avoid a perceivable slip where there could be location to location variations in friction level. They could be more vulnerable to a fall during this adaptation period when they are transitioning to a more slippery area. Gait adaptions to avoid a slip on slippery surfaces include increases in stance duration, stride time and step width, as well as decreases in stride length, walking speed, heel horizontal velocity, heel horizontal and vertical accelerations, heel and floor angle and utilized coefficient of friction (UCOF) (Swensen et al., 1992; Bunterngchit et al., 2000; Fong et al., 2005; Lockhart et al., 2007; Menant et al., 2009; Cappellini et al., 2010). The UCOF is the maximum coefficient of friction (COF) calculated from the ground reaction force (GRF) obtained with a force plate when walking on surfaces that could be slippery and represents the friction needed to walk on a surface that could be contaminated.

Human body movements and the contact force between shoe sole and floor reflect strategies in response to the conditions experienced at the shoe and floor interface beneath. Perception of slipperiness might dominate kinematics prior to stepping onto the surface. Continuous adjustments are necessary in order to assure that the strategies employed can actually prevent a slip (Cappellini et al., 2010), so all parameters could be interrelated and the

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relationships among them change as walking continues until a steady state is reached. Gait adaption when continuously walking back and forth on a 7 m long slippery surface 13 times was investigated by Cappellini et al. (2010). Their results showed that kinematic measurements had more variations in the first trial, but the basic features of walking on the slippery surface were already present in that trial. Walking speed, gait cycle time, percentage of stance and lateral hip displacement differed significantly when comparing the kinematics of the first and last trials.

Although gait adaptions to avoid a slip have been reported in the literature, participants in these studies were exposed to a limited area with a low ACOF, or to a very limited range of low friction conditions. Only the force plate areas were covered with the contaminants to generate the low friction areas in the results reported by Fong et al. (2005) and Lockhart et al. (2007). The participants in the study conducted by Lockhart et al. (2007) were exposed to the low friction area only once, with prior knowledge, to quantify gait adaptation rather than motor learning. In reality, people often have to take several steps in order to walk through a large slippery surface. Asaka et al. (2004) and Cappellini et al. (2010) used entire walkways with a low ACOF, but they exposed the participants to only one low friction condition. Swensen et al. (1992) exposed their participants to a section of low COF region, but they focused only on walking on narrow steel beams, not a normal gait. In reality, people are exposed to slippery conditions. Knowing how quickly they can adapt to different conditions and what strategies they use to ensure safe locomotion under these conditions could be very important in preventing slip and fall injuries.

A recent study by Lesch et al. (2016) exposed participants to different degrees of slipperiness generated with five floor types under three surface conditions for five trials and the participants rated their perception of slipperiness before and after walking on each walkway. These five floor types were selected based on subjective rating obtained in a pilot study conducted under dry conditions (Lesch et al., 2008) and some floor types were found to look more or less slippery than was suggested by their ACOF values. Their results showed that the rating before walking was a significant predictor of responses only for trial 1 and the rating after walking was a significant predictor of responses on trials 2 to 5 for heel strike angle, walking speed and step length. However, UCOF had a different pattern in that the rating after walking was a significant predictor of responses on all trials and the rating before walking was not a significant predictor for any of the trials. They also converted the perceived slipperiness rating into four different slipperiness categories ranging from 1 (not at all slippery) to 4 (extremely slippery) and compared the differences in dependent variables quantifying gait adaptation in trials in which the category was changed from one to another from before to after walking on the walkway with those in which there was no change in category as the baseline. When perceived slipperiness rating increased to a more slippery category from before to after walking on the surfaces, gait became more protective across the trials compared with those without a change in category, while gait became less protective for a rating change to a less slippery category. In the current study, these gait adaptation data were reanalyzed based on objective factors such as floor types, surface conditions and available coefficient of friction (ACOF) measured with a slipmeter. Furthermore, additional gait kinematic variables were included. These analyses would give more general pictures of the gait adaptation process from different perspectives and the values of dependent variables were compared.

2. Methods

Five different floor types and three different surface conditions were used in this experiment to create a wide range of slipperiness conditions.

2.1. Floor tile selections

The five floor types used in the current experiment were: (A) a standard quarry tile with raised-profiled tread lines perpendicular to the walking direction, (B) standard flat quarry tile, (C) vinyl composition sheet, (D) marble tile and (E) glazed porcelain tile. Detailed information about these floor types, referred to as types A to E, is listed in Table 1. These five different floor types were selected from 37 common floor types, evaluated in a previous study conducted under dry conditions, due to their distinctive features that represented different combinations of friction levels and perceptual cues to slipperiness (Lesch et al., 2008). This study was a part of a larger experiment to investigate the issues of measurement of slipperiness and perceived slipperiness rating (Chang et al., 2015; Lesch et al., 2016).

2.2. Walkway construction

A multiple floor walkway system was constructed. This system consisted of two moveable sections, each having five walkways covered with different floor types, the force plate area, and two stationary straight extensions at both ends as shown in Fig. 1. The extensions were covered with floor type B, the standard flat quarry tile. Each of the walkways in both moveable sections was covered with one of the floor types. To measure the GRF, two force plates (Model 9281C, Kistler Instrument Corporation, Amherst, New York, USA) were installed on a stationary portion in the middle of the whole walkway system between the two movable sections. As shown in Fig. 1, these two force plates were installed one right after the other along the length of the walkway on the right hand side in the direction of walking during biomechanics data collection. The force plate arrangement was intended to capture the GRF of the right foot during the trials. Even though there were no force plates on the left side of the walkway, additional force plate covers were made to cover this area so that the two sides looked the same. When a particular floor type was needed during data collection, both sections of the desired walkway were moved to align with the extensions and locked in place, and four force plate covers of the same floor type were secured to the walkway. Each section of the moveable walkway was approximately 2.44 m long and 0.81 m wide. The size of each force plate cover was approximately 60 cm by 40 cm. A straight walkway of approximately 6.08 m long and 0.81 m wide for a particular floor type was ready for data collection once the floor changes were completed. The extension at one end of the walkway where the participants exited after completing the five walking trials was approximately 2.44 m long, shown as the top section of Fig. 1. The other extension, where the participants initiated the walking trials, shown as the bottom section in Fig. 1, was

Table 1
Floor types used in the current experiment.

Floor type	Description
A	Metropolitan Ceramics quarry metrotread in Mayflower Red – 7731T
B	Metropolitan Ceramics quarry basics clear tones in Mayflower Red – 77310
C	Vinyl laminate with wood finish (Armstrong Rhythms in Olde Hickory – 92190)
D	Marble tile (Storm Cloud Grey)
E	Glazed porcelain tile with silver finish (Iris Ceramica Series: Metal 18 × 18 Color/Item: Titanium SKU No.: 745452)

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