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Heel contact dynamics in alternative footwear during slip events

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ABSTRACT

Introduction: Slips, trips and an induced loss of balance have been identified as the major causative factor for workplace injuries involving falls. Moreover, alternative footwear such as crocs and flip flops have been used in and around work places, especially with the usage of crocs in slip prone hospital settings. **Purpose:** The purpose of the study is to analyze the effects of alternative footwear [crocs (CC), flip-flops (FF)] and industry standard slip resistant shoes (LT) on heel dynamics during slip events.

Methods: Eighteen healthy male participants following a repeated measures design for each footwear condition, were tested for heel kinematics during normal dry surface gait (NG); unexpected slip (US), alert slip (AS) and expected slip (ES). A 3×4 repeated measures ANOVA was used to analyze the dependent slip parameters (heel slip distance-HSD & mean heel slip velocity-MHSV) at $p = 0.05$.

Results: Significant interactions between footwear and gait trials were found for HSD & MHSV, with significantly greater slip parameters exhibited by CC & FF compared to LT during US.

Conclusion: Alternative footwear (CC & FF) demonstrated greater slips, but were limited to slip events that were unexpected. With the knowledge and anticipation of slippery flooring conditions, participants were able to lower the slip parameters by kinematically modifying heel contact dynamics. The LT had significantly lower slip parameters and maintained a normal gait pattern for all slip trials, and demonstrates to be the choice of footwear for maneuvering slippery flooring conditions; while alternative footwear combined with unexpected slip events contributed to potentially hazardous and hazardous slips.

Relevance to Industry: Alternative footwear such as crocs are widely used in hospitals which are slip prone environments. This study provides evidence that these alternative footwear may predispose to hazardous slips and recommends the use of slip resistant footwear or slip resistant modifications to alternative footwear under known or unknown slippery conditions.

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1. Introduction

Injuries in and around workplace pose a significant burden to the health of human beings as well as to the financial losses to both the individual and the occupational organizations. Slips, trips and an induced loss of balance have been identified as the major causative factor for workplace injuries involving falls (Courtney et al., 2001; Redfern et al., 2001) and pedestrian accidents in the walkway have been identified as the second largest generator of unintentional workplace fatalities (Leamon and Murphy, 1995). The Bureau of Labor Statistics reported 15% of a total of 4693 workplace fatalities and a total of 299,090 cases of non-fatal workplace

injuries that were due to slips, trips and falls (STFs) (BLS, 2012). The annual cost of workplace injuries due to slips, trips and falls in the United States was estimated to be over 6 billion US dollars with an expected cost of \$43.8 billion by 2020 (Courtney et al., 2001). STFs occur as a result of failure of normal locomotion and failure of attempts at equilibrium recovery following an induced imbalance (Davis, 1983; Gauchard et al., 2001). These STFs can be induced by extrinsic or environmental factors such as the physical characteristics of the floor or ground surface such as the type, smoothness or roughness of the surface, compliance of the surface, the presence or absence of contaminants and the type of footwear and its interaction with the floor in the footwear-floor interface (Redfern et al., 2001; Gauchard et al., 2001); or by failure of the intrinsic-human factors such as aging, anthropometric features, gait speed, muscular fatigue and disorders of the musculoskeletal system and the perception of slipperiness of the floor (Gauchard et al., 2001; Redfern et al., 2001; Hanson et al., 1999).

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Footwear design features that have been shown to enhance sensory input or mechanical stability of the foot and the ankle and thereby ultimately improving balance and gait mechanisms include a hard sole, elevated boot-shaft or a high-collar and a lower mass (Chander et al., 2014; Perry et al., 2007); and footwear with more and deeper tread grooves have been shown to be slip-resistant and prevent slips (Li and Chen, 2005; Li et al., 2006). Conversely, footwear design features that include soft soles, elevated heels and a heavier mass have been shown to have lowered balance and gait performance (Menant et al., 2008; Divert et al., 2005; Bohm and Hosl, 2010). Moreover, anticipation of the slippery conditions, including attentiveness or alertness and mental workload can influence the outcome of slip events (DiDomenico et al., 2007). The perception and anticipation of a slip have been shown to reduce the possibility of slips with biomechanical modifications to gait (Chang et al., 2004; Cham and Redfern, 2002a).

Human gait is invariably affected by the coefficient of friction (COF) that exist at the footwear-floor interface. The slip propensity increases when the available COF is lower than the required COF for safe locomotion (Redfern et al., 2001). During normal dry surface gait, the heel movement has a characteristic pattern, where the heel rapidly decelerates just prior to heel strike following which the heel moves slightly forward (Perkins, 1978; Strandberg and Lanshammar, 1981; Redfern et al., 2001; Cham and Redfern, 2002a). At heel strike, the heel has been shown to have an instantaneous velocity in the forward direction (Perkins, 1978; Strandberg and Lanshammar, 1981) and some instances in a rearward direction (Cham and Redfern, 2002a), after which the heel reaches a minimum velocity and comes to a stop, over which the rest of the foot rolls over completing the midstance of a gait cycle. The time period during heel strike and 25 ms immediately post heel strike have been shown to be more crucial to development of an unrecoverable slip (McGorry et al., 2010) and the most hazardous slips often occur shortly after heel strike (<70–120 ms) (Lockhart and Kim, 2006).

The heel slip distance and heel slip velocity of the heel motion following heel strike in a gait cycle have been used to characterize slip types (Redfern et al., 2001). Micro-slips are characterized by heel slip distance of 1 cm–3 cm and are not perceived by the individuals and easily compensated for by the automatic postural system. Macro-slips are characterized by the slip distances between 3 cm and 10 cm, which will result in a loss of balance and may or may not result in fall, while slip distances greater than 10 cm are most likely to result a fall, (Perkins, 1978; Strandberg and Lanshammar, 1981, Redfern et al., 2001; Cham and Redfern, 2002a) and heel velocities of 0.5 m/s or higher have been shown to have an increased potential for a slip (Redfern et al., 2001). However, other research suggests that these values maybe too conservative (Brady et al., 2000), and only even greater slip distances and slip velocities are more likely to result in slip induced falls (Lockhart and Kim, 2006; Moyer et al., 2006). In other studies, Cham and Redfern (2002b) demonstrated slip induced falls when the slip distances were equal or greater than 10 cm and when slip velocities were equal or greater than 0.8 m/s (Cham and Redfern, 2002b) and Moyer et al. (2006) demonstrated slip induced falls with slip distances greater than 10 cm and slip velocities greater than 1 m/s (Moyer et al., 2006).

Preventing slips and slip induced fall accidents have been an important aspect of ergonomics research and have focused on slip-resistant properties of the footwear-floor interface. Footwear modifications including slip resistant soles have been mandated in occupational footwear by the Occupational Safety and Health Administration (OSHA) regulations and American National Standard Institute (ANSI). However, the impact of alternative footwear such as flip-flops and crocs which are commonly used among

pedestrians and few of the occupational environments such as slip prone hospital settings, have not been analyzed under slippery conditions yet. Furthermore, usage of flip-flops and crocs in and around the workplace as an alternative footwear due to its comfort and easy donning has grown in the recent years, further emphasizing the need to address the effect of these footwear on slip events.

Balance and gait mechanisms during normal locomotion and under slippery conditions have been studied extensively (Winter, 1995; Redfern et al., 2001) and consequently, there have been several studies that focus on the biomechanics of STFs which are the primary causative factors for falls in pedestrian population and especially in occupational environments, where there is a greater incidence of slips due to the environmental occupational hazards (Redfern et al., 2001; McGorry et al., 2010; Cham and Redfern, 2002a; Cham and Redfern, 2002b; Hanson et al., 1999; Perkins, 1978; Strandberg and Lanshammar, 1981). The effect of different footwear, different flooring conditions and the footwear-floor interactions on the biomechanics of gait and balance have also been identified (Li et al., 2006; Shroyer and Weimar, 2010; Perry et al., 2007; Menant et al., 2008; Divert et al., 2005; Bohm and Hosl, 2010). While extensive literature exists on biomechanics of balance, gait and slips and the influence of footwear on these, there is still dearth of literature on the effect of much commonly used alternative footwear on the biomechanics of gait and slips. Hence, the purpose of the study is to analyze the effects of alternative footwear [crocs with clogs (CC), thong style flip-flops (FF) and slip resistant low-top shoe (LT)] (Pictures 1–3) on heel contact dynamics (slip parameters) during dry normal gait (NG), unexpected slip (US), alert slip (AS) and expected slip (ES). We hypothesized that the slip parameters will be greater in alternative footwear: crocs and flip flops (CC & FF) compared to an industry standard low top slip resistant shoe (LT), leading to a greater potential for slips. We also hypothesized that the slip parameters will be greater during slip events compared to normal dry surface gait.

2. Methodology

2.1. Participants

Eighteen healthy male participants [Age: 22.28 ± 2.2 years; Height: 177.66 ± 6.9 cm; Mass: 79.27 ± 7.6 kg] completed the study. Participants who had any history of musculoskeletal injuries, cardio-vascular abnormalities, neurological disorders, vestibular disorders, under medications or any inability to walk and stand without support were excluded from the study. All participants were recruited through flyers approved by the University's Institutional Review Board (IRB). All participants read and signed the informed consent and also filled out the physical activity readiness questionnaire (PAR-Q) to rule out any of the above mentioned health complications and cleared for participation in the study.

2.2. Instrumentation

2.2.1. 3D motion capture

Vicon Nexus (Oxford, UK) 3D motion capture system with 12 infra-red T-series cameras was used to collect and analyze kinematic gait data. A lower body plug-in gait model from the Helen-Hayes marker system was used for the participant configuration and the kinematic data was sampled at 100 Hz and collected using the Vicon Nexus software.

2.2.2. Fall arrest system

A uni-track fall arrest system from Rigid Lines (Millington, TN); a lightweight horizontal rigid fall arrest track was used to prevent any undesired falls. Participants were attached to the fall arrest

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