Applied Ergonomics 66 (2018) 32–40

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Identification of heel strike under a slippery condition

Wen-Ruey Chang [a,*], Xu Xu [b]

[a] Chang WR Falls Prevention, LLC, Arlington, VA 22209, USA
[b] Edward P. Fitts Department of Industrial and Systems Engineering, North Carolina State University, Raleigh, NC 27695, USA

ARTICLE INFO

Article history:
Received 30 November 2016
Received in revised form
14 July 2017
Accepted 3 August 2017

Keywords:
Heel contact
High speed camera
Kinematics
Force plate

ABSTRACT

Kinematics at heel strike instant (HSI) has been used to quantify slip severity. However, methods to identify HSI remain ambiguous and have not been evaluated under slippery conditions. A glass force plate was used to observe the contact interface between shoe and floor under slippery conditions. HSIs identified from the video captured beneath the force plate and from the force plate and kinematics were compared. The results showed that HSIs identified with the video were closer to those identified with the normal force threshold (NFT) (9.0 ms ± 5.5 ms) than were most of those identified with kinematics. Slips with a longer distance travelled between NFT HSI and video HSI had a larger heel horizontal velocity (>0.8 m/s) and a smaller foot angular velocity (<100deg/s) at the NFT instant, and were still part of the forward swing. The results show that improved methods are needed over NFT to identify HSI, especially under slippery conditions.

1. Introduction

Data from the Liberty Mutual Workplace Safety Index (Liberty Mutual Research Institute for Safety, 2016) showed that the direct costs for disabling workplace injuries in 2013 due to *falls on same level* in the United States were estimated to be approximately 10.17 billion U.S. dollars or 16.4% of the total cost burden. In addition, *slip or trip without fall* accounted for 2.35 billion U.S. dollars or 3.8%. For falls on the same level, slippery floors, mostly caused by contaminants, are a critical factor (Chang et al., 2016). 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.

Heel strike plays a critical role in slips and falls on the same level (Leamon, 1992; Redfern and Rhoades, 1996; Redfern et al., 2001). Kinematics parameters at heel strike, such as heel strike angle, and heel horizontal and vertical velocities, are some of the measures to quantify the severity of slips (Redfern et al., 2001; Lockhart et al., 2003). For example, a significant correlation has been reported between heel contact velocity and friction demand, also known as the required coefficient of friction, ($p = 0.002$ and 0.01) (Lockhart et al., 2003; Kim et al., 2005) and between horizontal heel contact velocity and slip distance ($p = 0.0001$) (Lockhart et al., 2003). Heel movement around the instant of heel strike could be very important because it is the beginning of a slip event (Chang et al., 2016). Slipmeters have been used to mimic slip events which start from the instant of heel strike, so gait parameters starting from the instant of heel strike should be included as a part of reproducing slip events (Chang et al., 2016). Several methods for identifying a heel strike have been reported in the literature and they have resulted in different instants for the same event as summarized later in this section (Woldstad et al., 1998; Hreljac and Marshall, 2000; Hansen et al., 2002; Ghoussayni et al., 2004; O'Connor et al., 2007; Zeni et al., 2008; Desailly et al., 2009; Banks et al., 2015). A heel strike is preceded by a forward swing and is followed by a fast foot rotation (Perkins, 1978; Cham and Redfern, 2002). The forward swing, heel strike and fast foot rotation are very distinct movements. Heel strike is a short duration within a very fast continuous movement, so identification of even slightly different heel strike instants (HSIs) could lead to very different values for the gait parameters (Perkins, 1978; Cham and Redfern, 2002). Improved identification of HSI would allow us to identify the early phase of slip events, starting with heel strike, and identify the critical parameters.

The definition for heel strike has been vague. Perry and Burnfield (2010) defined heel strike as floor contact with the heel. Heel contact is another term in lieu of heel strike (Redfern et al., 2001). One of the typical criteria used in the literature to define a heel strike is the instant when the normal force reaches a threshold value such as 10 N (e.g. Lockhart et al., 2003). This method, based on

* Corresponding author.
E-mail address: wenruey.chang@gmail.com (W.-R. Chang).

http://dx.doi.org/10.1016/j.apergo.2017.08.004

the normal force threshold (NFT), has been considered as a reference for identifying heel strike when compared with methods based on kinematics (Woldstad et al., 1998; Hreljac and Marshall, 2000; Hansen et al., 2002; Ghoussayni et al., 2004; O'Connor et al., 2007; Zeni et al., 2008; Desailly et al., 2009; Banks et al., 2015).

Heel vertical movement has been used to identify HSI. Hreljac and Marshall (2000) were able to determine heel strike with an interpolation method to within 8 ms, on average, from that determined by the NFT by identifying the instant of the maximum heel vertical acceleration. Desailly et al. (2009) developed a filtered heel displacement method in which the heel motion was high pass filtered to amplify the contact discontinuities, thus the local maximum of the processed signal corresponded to heel strike. Their algorithm appeared to work very well for cerebral palsy children (1 ± 23 ms) in their study, but not as well for the healthy adults (27 ± 19 ms) when compared with the HSIs identified with the NFT.

Another approach to identifying HSI was based on the heel horizontal movement. Defining heel strike as the instant when the heel and hip reached a maximum distance apart, Woldstad et al. (1998) reported that the force level remained zero when the maximum distance was reached. Zeni et al. (2008) used similar approaches by defining heel strike as the instant when the distance between heel and sacral marker reached the maximum or the relative velocity between heel and sacral markers changed sign. They used 20 N as the NFT for the heel strike. Both algorithms introduced by Zeni et al. (2008) were able to determine 98% of heel strikes within 33 ms and 82% within 16.7 ms compared with that based on the NFT. Banks et al. (2015) defined heel strike as an instant when the distance between the stance ankle and the swing heel reached the maximum, developing a method which resulted in HSIs being detected within 3.2 ± 4.4 ms compared with the results obtained using a 10 N NFT. These HSIs were significantly closer to those obtained with NFT than those obtained with the methods by Zeni et al. (2008) (-20.6 ± 5.3 ms), Hreljac and Marshall (2000) (11.5 ± 5.3 ms) and Desailly et al. (2009) (-46.9 ± 12.9 ms) ($p < 0.0001$).

The currently published methods based on the NFT to identify the HSI through the force plate data do not account for conditions when a drag before heel strike occurs. Under ideal conditions, the reference based on NFT is appropriate. In some cases, however, the heel might drag on the floor during the final phase of the forward swing. This drag typically is followed by the inception of weight transfer to the leading foot and eventually leads to various movements after the heel strike as described by Perkins (1978). The drag of the heel on the floor surface can result in a slower rate of increase in the normal force when the normal force just exceeds the noise level of the force plate than a clean heel strike where no drag occurs. For this type of walking with a heel drag, the important instant is that at the inception of weight transfer. In the current study, the instant that the heel contacts the floor at the end of the swing phase is called heel contact and the instant at the inception of weight transfer is called heel strike. For walks with a drag, heel strike happens later than heel contact in a gait cycle and extraction of critical gait parameters at the instant of heel contact could, thus, be less relevant to slip and fall injuries under this circumstance. The drag prior to the heel strike was part of the forward swing with no substantial build-up of the contact force between foot and floor. This has no significant effect on what could happen after the heel strike and, therefore, should be ignored even though the shoe has contact with the floor. For those walks with a clean heel strike without any drag, the criterion to extract critical gait parameters based on heel contact is appropriate since the heel contact and heel strike are essentially identical. Critical questions in the investigation of slip initiations are, thus, how to identify the instant of a heel strike since heel strike is the beginning of a slip event and how to differentiate it from a heel contact.

McGorry et al. (2007) appeared to realize the limitation of a method based on the NFT. In their method based on normal force data proposed by McGorry et al. (2007), heel strike was the first instant in the stance phase that the normal force exceeded 5 N and had a slope of at least 2.4 N/ms within the subsequent 17 ms. Although this method was used to identify HSI of the data obtained with 21 participants in their study, the results obtained with this method have not been confirmed or compared with the results of other methods. In addition, this method has not been applied to the results obtained on slippery surfaces where the normal force build-up could be very different from that on dry surfaces.

The results of all these aforementioned kinematics methods were compared with those obtained from force plate data with different values for NFT based on the simpler definition of heel strike as the instant that the foot touches the floor. The reference based on NFT may have problems of its own. For example, in the case of a foot dragged at the end of the forward swing, the normal contact force could reach the threshold value for the heel strike before the actual heel strike event. Therefore, the accuracy based on kinematics data might not be as accurate as that reported in the literature. Multiple exposure pictures of slip events captured by Perkins (1978) showed a small vertical drop right before heel strike which may be a problem for the methods based on the horizontal movement. In fact, this drop might have caused the discrepancy that heel strike determined based the horizontal movement was mostly ahead of that based on the NFT as reported by Woldstad et al. (1998) and Zeni et al. (2008). Furthermore, these methods were developed from data collected on dry surfaces and have not been shown to work when a slip occurs.

In data collected solely with a metallic force plate or an above-ground motion tracking system, it is difficult to pinpoint the exact instant of a heel strike, especially under slippery conditions. An alternative is to simultaneously observe the movement from below ground level and measure the contact force via a clear glass force plate and video camera. The objectives of the current study were to observe via video recording and quantify foot movements during the initial phase of heel contact, in particular heel strike, under normal gait under slippery conditions through a clear glass force plate. The goal was to compare the instants of heel strike under slippery conditions obtained from the video images captured beneath the glass force plate with those obtained with the force plate and derived from kinematics obtained with a traditional motion tracking system.

2. Method

2.1. Participants

Thirty seven participants took part in this experiment. The exclusion criteria for screening participants were (1) current or history of neurological or musculoskeletal problems that might contribute to inability to walk stably, (2) history of back problem, sciatica, leg problems, (3) uncorrectable visual impairment, vestibular dysfunction, (4) problems with being on their feet or walking a good portion of the day. Signed informed consent to the experimental procedure approved by the New England Institutional Review Board was obtained from the participants before data collection. As the experiment progressed, only 20 participants, evenly divided by gender, had good data with all the data acquisition systems for the unexpected slippery trial. Only the steps onto the glass force plate covered with contaminant in these 20 trials were included in the analyses. The means and standard deviations