Applied Ergonomics 68 (2018) 72–79

Contents lists available at ScienceDirect

Applied Ergonomics

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

Assessing the effects of slippery steel beam coatings to ironworkers' gait stability

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A R T I C L E I N F O

Keywords:
Coefficient of friction
Perceived slipperiness
Maximum Lyapunov exponents

A B S T R A C T

Since ironworkers walk and perform their tasks on steel beams, identifying the effects of slippery steel beam surfaces on ironworkers' gait stability—which can be related to safety risk—is critical. However, there is no accepted or validated standard for measuring the slipperiness of coated steel beams, which makes evaluating and controlling for slipperiness a challenge. In this context, this study investigated the effect of the slipperiness of steel beam coatings on ironworkers' gait stability. Accordingly, to identify the relationships between coefficient of friction, perceived slipperiness, and gait stability—represented as the Maximum Lyaponuv exponent (Max LE)—an experiment was conducted with eight different surfaces and sixteen subjects with varying experience as ironworkers. The experiment's results indicate that the slipperiness of the various surfaces greatly affect ironworkers' gait stability while they walk on coated steel beam surfaces. In detail, the Max LE of two subject groups—experienced and inexperienced ironworkers—highly correlated with both the dynamic coefficient of friction values measured by following ANSI B101.3 and with the subjective rating scores of the inexperienced subject group. Unlike subjective rating scores—which were particularly incongruent among experienced workers—the Max LE of inexperienced and experienced subjects has a consistent pattern. This study result highlights an opportunity for using gait stability measurements to quantify and differentiate the safety risks caused by slippery coated steel beams in the future.

1. Introduction

Accidents caused by slips and falls on slippery surfaces present a significant safety issue in all built environments (Cattledge et al., 1996; Chi et al., 2005; Huang and Hinze, 2003). The construction industry is at particular risk for slips and falls due to the prevalence of unsafe surface conditions such as uneven ground or debris, muddy conditions, and narrow and slippery surfaces. Among all of the trades in the construction industry, ironworkers have the highest fall risk (Baradan and Usmen, 2006): While the overall fatality rate across construction occupations is estimated to be approximately 0.5%, ironworkers face a higher likelihood of fatality (3.11%–31.1 per 1000 full-time equivalent staff) (CPWR, 2013). In particular, working on narrow steel beams coated with paint or other protective coatings represents a major cause of ironworkers' falls ((Occupational Safety & Health Administration [OSHA], 1997). Such protective coatings or paints are generally used on structural steel that is exposed to highly corrosive materials (e.g., construction of mills and chemical plants) or exposed to varying weather conditions (e.g., construction of stadiums) (Di Pilla, 2004). In addition, moisture, snow, or ice on coated steel compounds the hazard (OSHA, 1998). While the use of such coatings is reasonable for maintaining the steel beams, the paints or protective coatings usually increase the slipperiness of the steel surfaces and present a slip and fall hazard to ironworkers who walk on these surfaces.

In response to this concern, the U.S. OSHA published a new standard for steel erection work—29 Code of Federal Regulation Subpart R (2001 final rule, 66 FR 5196) (OSHA, 2001)—which includes a slip–resistance requirement for the painted and coated top walking surface of any structural steel member installed after July 18, 2006 (OSHA, 2006a). However, this slip resistance provision was revoked in 2006 (71 FR

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https://doi.org/10.1016/j.apergo.2017.11.003
Received 1 June 2016; Received in revised form 3 November 2017; Accepted 4 November 2017

2879) since there had been no significant progress regarding (1) the suitability of the test methods referenced in the original provision for evaluating the slip resistance of wetted, coated skeletal structural steel surfaces, and (2) the availability of coatings that would meet the slip resistance requirements of the original provision (OSHA, 2006b). In particular, the testing methods referenced in the original provision, American Society for Testing and Materials (ASTM) F1677 (ASTM, 2006a) and F1679 (ASTM, 2006b), were withdrawn for failure to include approved precision and bias statements. Consequently, there is yet no general approach for quantifying slippery surface risk in ironwork except ironworkers' subjective surface slipperiness ratings (Swensen et al., 1992). However, the results of subjective surface slipperiness ratings are hardly acceptable for regulating the use of specific coating types., since they are often affected by an individual's visual perception of color, size, shape, texture gradient; physical characteristics (including height, weight, body balance, etc.); and familiarity, experience and personal bias with steel surfaces.

Quantifying biomechanical responses to slippery surfaces may provide an alternative way to assess the risk of slippery surfaces to human behavior during locomotion (Chang et al., 2017). Several previous studies have already shown that slippery surfaces affect gait patterns on floor surfaces (Cham and Redfern, 2002; Fong et al., 2009; Li, 1991; Menant et al., 2009; Yang and Hu, 2009). Moreover, it has been well known that there are significant relationships between gait patterns (*i.e.*, gait stability) and slip-related accidents (Bhatt et al., 2005, 2006, 2011; England and Granata, 2007). In the context of steel erection tasks, where walking is restricted on narrow steel beams, gait patterns may be more susceptible to the perturbations caused by the slippery surface. Despite the large number of fatalities in the ironwork industry, the effects of the slippery coated steel beams on gait patterns have rarely been studied. Although Swensen et al. (1992) investigated the relationship between subjective perceived slipperiness and the coefficient of friction (COF) of coated steel beams, the gait pattern was not incorporated in their investigation. To this end, this study investigated the effects of the slipperiness of steel beam coatings on subjects' gait stability measurements. In particular, this study used Maximum Lyaponuv exponent (Max LE) to measure the gait stability of subjects; Max LE had been used as one of the metrics that is capable of measuring the gait stability of human subjects in the clinical domain (Dingwell et al., 2001; Hurmuzlu et al., 1996; Kang and Dingwell, 2008). In addition, Jebelli et al. (2014) used Max LE in studying the effects of ironworkers' high-risk walking tasks on their gait stability. Specifically, Max LE values obtained from walking on different coatings were compared to the perceived slipperiness of subjects and to the dynamic coefficient of friction (DCOF) measured using the American National Standards Institute (ANSI) B101.3 standard.

2. Methodology

To examine the relationship among perceived slipperiness (subjective rating), DCOF and Max LE, we conducted a series of experiments with diverse conditions that involved human subjects. Using the methodology developed by Jebelli et al. (2015, 2014), IMU sensors were attached to the human subjects' right ankle—past research has shown that the location was being sensitive to changes in dynamic stability (Liu et al., 2008), and these sensors transmitted gait information (acceleration data) to a laptop. After each task, each subject was asked to provide his/her subjective assessment of the slipperiness of each surface, and each subject's gait stability was calculated by using Max LE.

2.1. Subjects and procedures

Sixteen healthy subjects—five experienced subjects who have worked as ironworkers over five years and 11 inexperienced subjects who are graduate students—participated in this research after giving informed consent approved by the University of Nebraska Institutional Review Board. None of the subjects have any clinical conditions that could affect their gait balance. Table 1 summarizes the physiological information provided by the participants. Among the physiological information, the weight and shoe size of the subjects were assessed at the experiment site, and their height and age were self-reported by subjects.

Table 1
Subject sample information.

Statistical parameters		Height (cm)	Weight (kg)	Shoe Size (US size)	Age (years)
Inexperienced Subjects	Mean	172.9	73.5	9.4	27.6
	Median	170.3	72.1	10	29
	Standard Deviation	5.1	10.9	1.1	4.51
	Min value	162.7	59.4	7.5	19
	Max value	180.0	99.8	11	35
Experienced Subjects	Mean	172.9	90.3	10.5	33.6
	Median	180.0	72.1	11	34
	Standard Deviation	7.6	8.2	1.7	3.51
	Min value	167.8	77.1	8	30
	Max value	185.1	99.8	12	37

Each subject performed eight tests. Since consecutive trials of walking on the same dry and wet surfaces may cause the carryover effects—which can affect a subject's gait (Bagley et al., 1991; Hausdorff et al., 2007), the authors tried to minimize the carryover effects in gait and perception by randomizing the order of trial. The order of the trials for the different types of coatings—though not the dry and wet conditions—was randomized; the dry and wet conditions of each coating were not randomized due to the logistics of the experiment. In addition, there was 2 min break between each trial. A subject walked on four dry coatings in a randomized order and then walked on four wet coatings in a randomized order.

The selected types of coatings were: 1) raw steel without any paint ("Raw Steel"), which stood as a control group (Test 1; see Fig. 1-a); 2) gray primer ("Primer"), which is one of the most common epoxy primer coatings (Test 2; see Fig. 1-b); 3) electrocoating using acrylic material ("Electro"), which local ironwork contractors identified as slippery and as possessing a safety risk (Cory Lyons, personal communication) (Test 3; see Fig. 1-c); and 4) anti-corrosion epoxy-based paint ("Epoxy"), since many ironworkers claim such epoxy-based paints are slippery (Dong and Yu, 2009) (Test 4; see Fig. 1-d).

In terms of the experimental process, 17 m-long (60 feet-long) steel beams were installed at a slight height off the ground (5 cm), and for each test, participants walked on the corresponding steel beam for 2 min at whichever speed they deemed their most comfortable walking speed. To allow participants to prepare for the experiment, we provided the test procedure to them a week before they came for data collection. This project used a traditional subjective rating test to investigate the perceived slipperiness of each steel beam's surface conditions. Each subject was asked to assess the slipperiness of the surface after each walking test. Subjects were asked to determine the slipperiness on a 1-10 scale (ten point Likert scale), with 1 as "not slippery at all" and 10 indicating an "extremely slippery" surface. Also, before starting the data collection, an instructor showed the subjects a demo of each task and answered any questions. Fig. 1 shows different tests and the experimental setup.

2.2. DCOF measurement

To measure the DCOF values of the selected coatings, this study used a BOT-3000E device under the standard of the American National Standards Institute (ANSI) B101.3 (ANSI 2012)—a test method for