Applied Ergonomics 59 (2017) 460–469

Contents lists available at ScienceDirect

Applied Ergonomics

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

Evaluation of a “walk-through” ladder top design during ladder-roof transitioning tasks

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ARTICLE INFO

Article history:
Received 8 March 2016
Received in revised form
6 October 2016
Accepted 11 October 2016

Keywords:
Ladder
Fall
Stability

ABSTRACT

This study evaluated the effect of an extension ladder “walk-through” top design on kinetic and kinematic behaviors and the outward destabilizing forces induced on the ladder during transitioning at elevation. Thirty-two male participants performed stepping tasks between a ladder top and a roof at simulated elevation in a surround-screen virtual-reality system. The experimental conditions included a “walk-through” and a standard ladder top section supported on flat and sloped roof surfaces. Three force platforms were placed under the ladder section and in the roof to measure propulsion forces during transitions. A motion measurement system was used to record trunk kinematics. The frictional demand at the virtual ladder base was also calculated. The results indicate that under optimal ladder setup (angle 75.5 °), the frictional demand at the ladder base remains relatively small for all experimental conditions. Also, the “walk through” ladder top eased the ladder-to-roof transitions but not the roof-to-ladder transitions.

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1. Introduction

Ladders are one of the most widely used means of access to elevated surfaces; they are simple and relatively inexpensive, but, there is a persistent safety hazard involved with their use. There were 132 fatal falls from ladders for the U.S. labor force in 2010 (BLS, 2012). These incidents occurred most often (52%) in the construction industry. In addition, in 2010 there were 14,710 nonfatal injuries from ladder-related falls resulting in days away from work, 28.3% of which were in the construction industry (BLS, 2013). Extension or straight portable ladders are commonly used in construction work for variety of tasks, and frequently for access to elevated structures such as residential roofs.

Transitioning to or from a ladder at elevation was identified as one of the most dangerous activities for the ladder users (Hsiao et al., 2008). Ladder transitioning accounted for 14% of all ladder fall fatalities, in a study of OSHA detailed reports of 277 portable ladder fatalities in the period 1984 to 1998 (Shepherd et al., 2006). An earlier study of 123 occupational non-fatal ladder-falls resulting in admission to a hospital emergency room, and recorded by the National Electronic Injury Surveillance System (NEISS), found that approximately 6% of the falls were associated with transition to or from a ladder (Cohen and Lin, 1991).

During a transition, the ladder users transfer their weight while stepping between the top of the ladder and the supporting transitioning structure, e.g., a roof surface; and thus applying forces on the ladder with a significant horizontal component. An earlier epidemiological study concluded that the horizontal force created by transitioning onto or from ladders was often the primary reason for ladders overturning or moving (Cohen and Lin, 1991). In a laboratory evaluation study on ladder transitioning, Clift et al. (2006) estimated low stability indices for tipping sideways, flipping, and losing top contact, but relatively high stability index for slide-out at the base.

Research on ladder transitioning at elevation has been relatively limited due to the associated risk of injury. To protect the participants, Clift et al. (2006) used fall protection equipment, which is not typically used with portable ladders. Recently, the innovative technology of virtual reality (VR) allowed recreating dangerous height environments in the lab (Simeonov et al., 2005) and performing fall prevention research in a controlled environment without the use of fall protection. Examples of fall prevention research using VR technology augmented with real structures include studies on scaffolding and roofing safety (Hsiao et al., 2005; Simeonov et al., 2008). The application of VR augmented with real ladder sections may be beneficial as unique novel approach for safe

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http://dx.doi.org/10.1016/j.apergo.2016.10.008
0003-6870/Published by Elsevier Ltd.

evaluation of new ladder top designs and accessories during transition tasks at elevation.

Modifying the ladder top design is one suggested direction for reducing the ladder sideway-tipping risk and improving the safety of a transition task. For example, it is believed that a "walk-through" (WT) ladder top design, which can be achieved by providing handrails that extend from the ladder, will be a safer alternative and will allow for easier and safer transition. Several "walk-through" devices, attachable as accessories to the top of the ladder and providing hand-rails or hand-holds that extend from the ladder, have been proposed (Ellis, 2000; Clark and Feik, 2008; Hsiao et al., 2010; Smith, 2011), and some of them are available as products on the market.

Slipping of ladder base (slide-out) is another common cause of falls associated with the use of extension ladders (Hsiao et al., 2008). The likelihood of an extension ladder base slipping depends on factors such as, the angle of ladder inclination, the coefficient of friction between the ladder base and the supporting surface, and the magnitude and location of the static and dynamic loads on the ladder (Pesonen and Häkkinen, 1988). Earlier analytical studies have demonstrated that loads applied close to the top support of a straight or extension ladder result in the highest risk of ladder slide out (Hepburn, 1958).

While the "walk-through" design concept appears promising in reducing sideway-tipping risk, it may introduce an increased push-out force during a transition and thus an increased risk of a ladder-base slide-out. In addition, the impact of a "walk-through" design on human kinetics and kinematics as an indicator of usability has not been systematically assessed. The objective of this study was to evaluate the effect of a ladder "walk-through" top design on kinetic and kinematic behaviors and the outward destabilizing forces induced on the ladder during transitioning at elevation.

2. Method

2.1. Participants

Sixteen experienced male ladder users with average age 39.9 (S.D. = 9.4) years, average weight 87.6 kg (S.D. = 16.8 kg), and average height 184.3 cm (S.D. = 6.1 cm) and sixteen inexperienced male participants with average age 32.5 (S.D. = 12.0) years, average weight 81.6 kg (S.D. = 12.0 kg), and average height 177.9 cm (S.D. = 4.2 cm) were recruited from the Morgantown, WV area. The experienced ladder users were workers with more than one year of job-related extension ladder use and the inexperienced participants had no job-related experience with extension ladders. Potential participants with the following medical history and/or conditions were not eligible for the study: acrophobia, height vertigo, history of dizziness, neurological disorders, and abnormal and uncorrected vision. Potential participants on medications (such as, for hypertension, tranquilizers, antidepressants, antihistamines) that can impair their balance or alter their reactions, perceptions and judgments were also excluded from the study. Approval to participate was based upon successful completion of a Screening Questionnaire and an Acrophobia Questionnaire (AQ) which were administered before starting the tests. Potential participants who score more than 50 points on the AQ were disqualified for the study (even though they do not recognize themselves as acrophobic) since the average scores among individuals without a pronounced fear of heights commonly fall below 30, while average scores among acrophobic populations commonly fall above 50 or 60 (Menzies and Parker, 2001; Jackson, 2009). Potential participants not approved for the study were informed of the reasons for such a decision. All participants gave informed consent and were compensated as approved by the Institutional Review Board of NIOSH.

2.2. Experimental setup

The study was conducted in a surround screen CAVE-type virtual reality (VR) system at the NIOSH Virtual Reality Lab. The virtual environment of elevation was augmented with a short section of a real ladder (the ladder physical model) and a real partial roof structure, which were positioned on the floor (the lower screen) of the VR system (Fig. 1 a). The VR system displayed interactive images of elevated construction site, i.e., a view over the edge of a roof. The interactive images included nearby surrounding buildings and other landscape details, as well as the virtual portion of the ladder (virtual ladder) which extended down from the floor and was supported on the virtual ground (Fig. 1b). The virtual portion of the ladder was well aligned and blended with the real section of the ladder, which extended from the floor at 75.5 °, and was supported at the edge of the roof section (Fig. 1c). The roof section (1.83 × 1.83 m) had an adjustable surface equipped with pneumatic actuators, and could quickly and easily be set at 0° or 18° slope. The roof surface was completely covered by black slip-resistant material which mimicked a shingled roof. The roof edge was at 0.46 m above the floor, while the ladder section was set so that the second rung was slightly above (0.1 m) the roof edge. This setup matched the OSHA Standards - 29CFR Safety and Health Regulations for Construction subsection 1926.1053 - Ladders (OSHA, 2015) that the ladder extended at least 0.9 m above the upper landing surface to which the ladder is used to gain access.

2.3. Experimental procedure

The participants were briefed about the study objectives, methods, procedures, and potential risks. The participants then changed into tightly fitting clothes, socks, and work shoes with slip-resistant soles provided by the laboratory, to allow the accurate measurement of body movement by attached markers. Researchers attached standard spherical (14 mm) reflective markers to the

Fig. 1. Experimental setup in the Virtual Reality system. (a). Physical model of a roof and a walk-through ladder top – in the CAVE VR system; (b). Sloped roof integrated in a virtual environment; (c). View over the edge of a two-story roof at the "hybrid" real-virtual model of extension ladder.