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Smoke Hood Design Considerations for Stairwell Evacuation

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Abstract

In a fire emergency, personal escape devices (smoke hoods) may be necessary to provide filtered breathable air ensuring that the evacuee has a reliable air supply to facilitate evacuation. The objective of this study was to evaluate the effects of wearing a smoke hood on vision (field-of-view) and evacuation time during stair well evacuation. Ten college students (mean age = 27.7 ± 8.5 years) were tested for their ability to fully see the stair treads in front of them, with and without the smoke hood. Subjects were also evacuated down an eight story flight of stairs (ten story building) wearing an inertial measurement unit (IMU) motion capture system. Subject motions were recorded and analyzed for evacuation times. Results indicated a significant reduction in one's 'field of view' directly in front of their feet when wearing the tested smoke hood ($p < 0.001$). The ability to see where one is walking (stepping) is useful to unimpeded locomotion on flat level surfaces, and is of even greater importance when descending stairs. Evacuation times with the smoke hoods were 21.5% longer than the no smoke hood condition. This result may suggest that subjects need a higher level of concentration to successfully locate and step on the next tread, and experience reduced speed, increasing the evacuation time ($p < 0.001$).

Keywords: Evacuation, Inertial Sensors, Smoke Hood, Stairwell, Time Study.

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Introduction

Fifteen thousand seven hundred (15,700) fires are reported annually in United States high-rise buildings, contributing to 53 deaths, 546 injured, and $235 million in direct property damage (Hall Jr, 2013). High-rise building fires are considered especially dangerous due to the potentially high number of occupants involved (Ronchi & Nilsson, 2013).

The traditional method of evacuating high-rise buildings in case of an emergency is by stairwells. Several studies have been performed to investigate factors that impact stairwell evacuation, such as the design of the stairs (J. Pauls, 2002; J. L. Pauls, Fruin & Zupan, 2007), the behavioral aspects of evacuees (Boyce, Purser & Shields, 2012), the effect of merging streams (Edwin R. Galea, Sharp & Lawrence, 2008), and evacuee fatigue (Averill et al., 2005; Edwin R. Galea et al., 2010). Other studies that evaluate occupant movement in building evacuation have also been reviewed and summarized (Peacock, Averill & Kuligowski, 2010).

Most fire deaths are not caused by burns, but by smoke inhalation. Often, smoke incapacitates so quickly that people are overcome and cannot make it to an otherwise accessible exit. Personal protective equipment such as a smoke hood may be critical to ensuring a sufficient supply of breathable that allows enough time for occupants to evacuate safely via available exits. In tall buildings this usually involves egress via stairwells. Aspects of evacuation associated with smoke hoods, however, have not been well established to date. Specifically, there is a lack of knowledge in how wearing a smoke hood might affect stair well evacuation time. The purpose of this study was to evaluate the effects of wearing a smoke hood on vision (field-of-view) and evacuation time during stairwell evacuation.

Method

Ten (N=10) college aged students (mean age = 27.7 ± 8.5 years; range 22-51) participated in the study. Subject demographics, stature and segmental limb length (for use in the biomechanical model) were collected. The study, performed as a portion of an academic class, was [retroactively] approved by the Auburn University (AL, USA) Institutional Review Board (IRB).

Smoke Hood

Smoke hoods are designed by manufacturers in many different styles and price ranges. A recent (May, 2016) internet search (Yahoo, 2016) included (partial listing) the images shown below (Figure 1).

Figure 1. *Internet Search for Smoke Hood Images*

Smoke hoods generally consist of a head cover that seals the breathing area, an assembly that filters/absorbs toxic gases (HCL, SO_2, HCN, and CO) and particulates, and includes some type of transparent 'window' that allows for evacuee vision. For this study, a KIKAR XHZLC 60 Fire Escape Mask (Figure 2) was selected, as this design contained a prominent filter assembly protruding from the lower front of the mask. As stated by the manufacturer of this smoke hood: "this respirator is intended for applications in governmental locations, hotels, offices buildings, forests, airports, department stores, banks, ships, post offices, power industry, telecommunications, subways, recreation centers, refineries and chemical industry, etc. as an essential breathing-protective device for personal safety in fire accidents."

Figure 2. *KIKAR XHZLC 60 Fire Escape Mask*

Motion Capture System

A commercially available inertial sensor-based motion analysis system, the Xsens MVN BIOMECH system (Xsens Technologies BV, Enschede, Netherlands) (Roetenberg, Luinge, & Slycke, 2009) was used in the evacuation study. It is a whole-body kinematic measurement system consisting of 17 sensors attached to the major segments of the human body (forearm, upper arm, trunk, etc.). Individual subject anthropometric data were used to create a rigid link biomechanical model based on information collected from the sensors. The output of this biomechanical model is a simulated estimation of the human motion during stairwell evacuation.

Neck Flexion Measurement Unit

An inertial measurement unit (Yost Labs, Dayton, Ohio) was used to calculate the neck flexion angle in the vision (field-of-view) test. The accelerometer-based inclination angle estimates subject neck flexion and was calculated with respect to the gravity vector.

Experiment Procedure

To evaluate the effects of wearing a smoke hood on vision (field-of-view) and evacuation speed on stairwells, two issues were addressed:

- Vision (field-of-view) study: The ability to see all or part of the stair tread(s) directly in front of the subject when descending stairs.
- Evacuation time study: Quantifying the evacuation speed with and without smoke hood usage.

Vision (field-of-view) Study

The question being addressed is whether or not wearing a smoke hood reduced ones' vision (resulting in fewer visible stair treads directly in front of the subject), more (or less) than the non-smoke hood condition (right panel in Figure 3). Subjects stood facing forward and affixed to an immobilizing device which was positioned securely on a landing atop a staircase (center panel in Figure 3). A randomized number set was placed on each stair tread in front of the subject (left panel in Figure 3).

Figure 3. *Vision (field-of-view) Study*

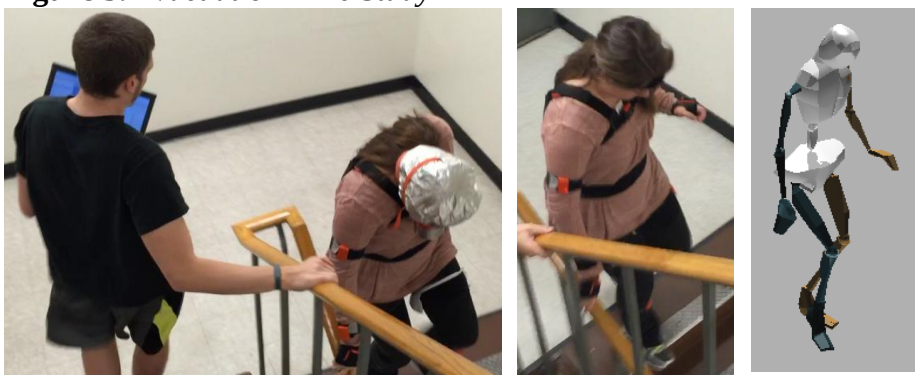
Subjects were asked to identify which random number (left panel in Figure 3), defacto stair tread, they could fully see before/after fully flexing (bending) their neck (Figure 4). The number of stair treads (directly in front and closest to them) that subjects *could not see* and their neck flexion angles were recorded.

Figure 4. *Subject with/without the Smoke Hood*

Evacuation Time Study

Each subject walked/evacuated down a ten (10) story flight of stairs (with/without a smoke hood) while wearing an Xsens inertial measurement unit based motion capture system (Figure 5). Subject motions, positions, and times were recorded by the system and used for subsequent evacuation time calculations.

Figure 5. *Evacuation Time Study*



Paired t-tests were performed to evaluate the effect of the smoke hood on vision (field-of-view), maximum neck flexion angle, and evacuation time.

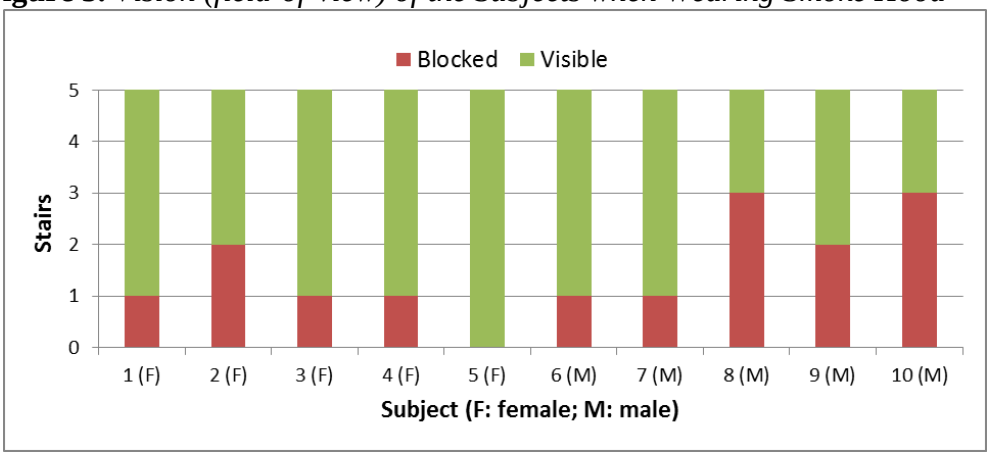
Results

Vision (field-of-view) Study

All ten subjects reported being able to see all of the treads on the descending staircase directly in front of them when not wearing the smoke hood. Conversely, nine of ten subjects' (90%) reported reduced vision (field-of-view) with 1.5 ± 0.97 stairs obscured when wearing the smoke hood, as they could no longer see all the stair treads directly in front of them.

Results indicate that the smoke hood's impact on maximum neck flexion angle was not significant, $p = 0.244$. However, wearing the smoke hood did show significant impact on the subjects' ability to see all the stair treads directly in front of them ($p < 0.001$).

Figure 5. *Vision (field-of-view) of the Subjects when Wearing Smoke Hood*

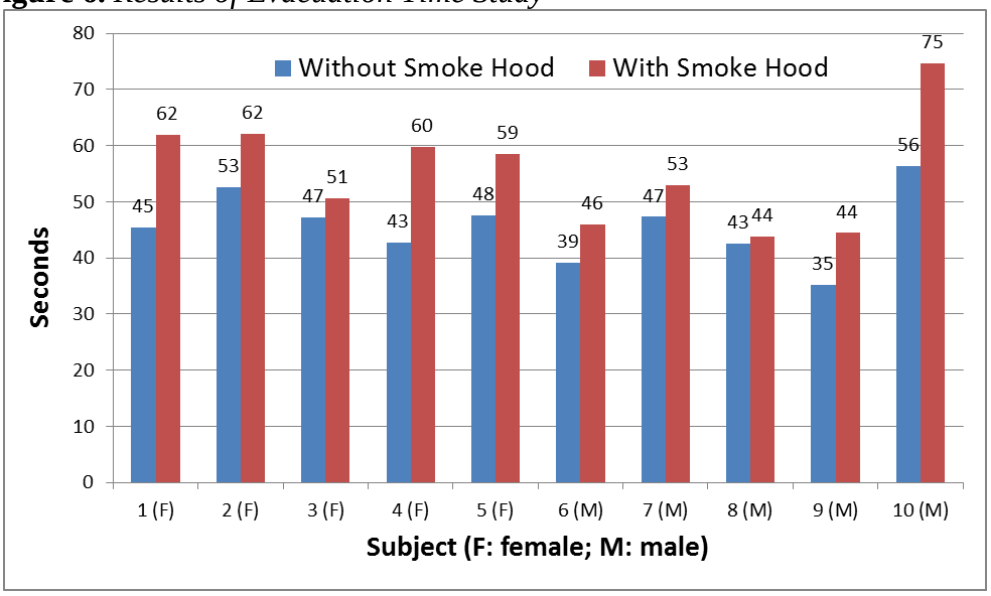


Evacuation Time Study

To eliminate the effect of acceleration/deceleration at the beginning/end of the stairwell decent evacuation trial, the evacuation time calculation was based on the 8th to the 2nd floor (excluded the 10th and 1st floors).

The results showed that it took longer to evacuate when wearing a smoke hood compared to the no smoke hood condition (Figure 6) ($p < 0.001$). All ten (10) subjects took longer to evacuate with the smoke hood. The mean additional time spent by the subjects' while wearing the hood was 10.0 seconds, which equates to a 21.5% increase in evacuation time. One-way ANOVA was performed to test the impact of gender on evacuation time; the results showed that it was not statistically significant with/without wearing a smoke hood with p-values of 0.341 and 0.476 respectively.

Figure 6. *Results of Evacuation Time Study*



Discussion

Studies and/or simulation models exist that evaluate different factors that might affect the stairwell evacuation time in a fire emergency (Peacock, Averill & Kuligowski, 2010). However, personal protective equipment that may be worn by evacuees has generally not been considered in these studies or models. In high-rise buildings, the necessity of wearing smoke hoods to ensure a safe atmosphere during the evacuation process is likely since it may take in excess of ten (10) minutes for people to evacuate from a 50^{+} story building. Therefore, it is important to understand how a smoke hood may effect evacuation times. Based on the results of this study, it is clear that wearing a smoke hood (at least the model tested in this study) results in increased evacuation times compared to the no smoke hood condition. One potential explanation for these results is the reduction of vision (i.e., not being able to see the next stair tread(s) one is

trying to step on). This may suggest subjects need a higher level of concentration to successfully locate and step on the next tread, experiencing reduced speed, and increasing the evacuation time. Other factors that might contribute to the reduced evacuation speed, such as the breathing resistance from the smoke hood, were not evaluated in this study.

Limitations

The following study limitations are acknowledged:

1) Only one smoke hood, a KIKAR XHZLC 60 Fire Escape Mask, was used in the study.
2) No level of subject concern or fear was present during the evacuation study.
3) Limited sample size (N=10).
4) No obstacles were present which might accentuate differences between the tested and control conditions.

Conclusions

The design of KIKAR XHZLC 60 Fire Escape Mask (as tested) does impact the wearer's vision (field-of-view) while being used, contributing to longer evacuation times, compared to the no smoke hood condition. This additional time is thought to be due to evacuees requiring more attention to locate, position, and balance themselves during decent. Smoke hood designers, and manufacturers should consider the location and size of all mask components that may lead to a reduced (field-of-view) while traversing stairs. Individuals and organizations that procure or make recommendations for purchasing smoke hoods should consider the same factors as well.

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