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Characterizing posture and associated physiological demand during evacuation

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ABSTRACT

Crawling is recommended for accessing breathable air and avoiding gases during severe fire evacuations. Few studies have evaluated the physiological burden associated with crawling, but those that have agree that crawling places high physiological demands on the body. Furthermore, with the exception of walking upright, the effect of locomotion modalities on the speed of evacuation is sparsely researched. This study evaluated distance, velocity, and the physiological costs of evacuating using different locomotion methods. Twenty-four (24) college students (12 M/12F) traveled up to 91.44 m (m) in different postures: Upright Walking (UW), Stoop-Walking (SW), Foot and Hand Crawling (FHC), Knee and Hand Crawling (KHC), and Low Crawling (LC). Crawling velocities were significantly slower than bipedal velocities ($p < 0.05$). Of the three crawling postures, FHC was faster ($p < 0.05$) than both KHC and LC. Average velocities for FHC, KHC, and LC were 1.20, 0.84, and 0.77 m/s (m/s), respectively. Velocities in all crawling postures decreased substantially after the first 9.14 m of travel. The average maximum crawling distance measured in this study was < 76.2 m. Physiological results demonstrated that crawling was more physically demanding than walking, represented by higher heart rates (HR), rates of oxygen consumption (VO_2), ventilation rates (V_E), and respiratory exchange ratios (RERs). Crawling was perceived by subjects to be much more difficult than walking, with many subjects unable to complete the 91.44 m course. Results of this study should be considered in the evaluation of current evacuation recommendations and in the design of future evacuation routes.

1. Introduction

According to the National Fire Protection Association (NFPA) (2015), most fatalities associated with fires are caused by smoke inhalation rather than direct burns. An analysis of fire deaths between 2003 and 2007 suggested that more than 80% of fatalities were the result of toxic and hot gas inhalation, resulting in respiratory tract damage or asphyxia due to insufficient oxygen. As fire propagates inside a structure, it consumes most of the available oxygen and generates hot toxic gases, which rise and begin to fill the habitable space from the ceiling down. OSHA (2015) has defined breathing zone as an area "… within a 25.4 cm (cm) radius of the worker's nose and mouth." The deterioration of environmental conditions in terms of toxic gases, heat and smoke, alters occupants breathing zones, potentially impeding them from using normal bipedal locomotion to evacuate. In such circumstances, humans are forced to seek and adopt atypical locomotive behaviors for survival.

The NFPA (2015) advises evacuees to avoid toxic gas inhalation and access breathable air by crawling low under smoke during evacuation from severe fires. Staying low under smoke also provides evacuees with improved vision to search for exit routes. A handful of previous studies have considered crawling activities in an evacuation context (Cao et al., 2014; Kady and Davis, 2009a,b; Muhdi et al., 2006; Nagai et al., 2006). These studies agree that crawling causes a significant decrease in velocity compared to walking. Muhdi et al. (2006) reported normal knee and hand crawling speed at 0.71 m/s (m/s), and maximum knee and hand crawling speed at 1.47 m/s. Nagai et al. (2006) reported average individual knee and hand crawling speed at 0.73 m/s, which was significantly slower than the upright walking speed (1.20 m/s) measured in their study. With the exception of knee and hand crawling, no other crawling techniques applicable to evacuation have been reported. Understanding the performance capabilities and limitations of various locomotive techniques is critical for designing optimal evacuation routes. Recent International Building Code (ICC) (2015) standards require that the distance to an exit should not exceed 76.2 m (m) if a sprinkler system is in place. However, there is no clear evidence that humans can actually crawl such a distance. Accordingly, one purpose of this study was to investigate the effects of different locomotive postures,

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required by breathing zone restrictions, on velocity and maximum travel distance.

Similarly, limited research has examined the physiological effects of atypical locomotion on evacuees. Previous studies that investigated physiological demands of bipedal activities (walking, jogging or running) established that walking is much less physiologically demanding than other bipedal locomotive techniques (Dill, 1965; Flynn et al., 1994; Francis and Hoobler, 1986; Jones et al., 1984; Fudge et al., 2007). Oxygen consumption rates (VO_2) for walking in most previous studies were reported at approximately 20 mL/(kg·min^{-1}) and average heart rates (HR) measured approximately 100 bpm (Dill, 1965; Jones, et al., 1984; Mattsson et al., 1997; Martin et al., 1992).

Literature also suggests that crawling results in significant physiological demands as well as physical discomfort (Moss, 1934). Gallagher et al. (2011) observed significant differences in locomotion performance and physiological demands among stoop-walking, 2-point crawling (only knees), and 4-point crawling (using knees and hands), when moving in restricted spaces. Average HR for 4-point crawling measured in their study was significantly higher than stoop-walking and 2-point (knees only) crawling. A study entitled, "Metabolic Costs of Stoop Walking and Crawling" performed by Morrissey et al. (1985) demonstrated that as the task posture became more stooped, there were marked increases in metabolic costs. A master's thesis by Davis (2011) entitled, "A Comparison of Physiological Effects of Traditional Walking Locomotion to Crawling" measured the metabolic costs of walking and knee and hand crawling activities. Davis (2011) conducted this study on a treadmill and evaluated HR, VO_2, ventilation rate (V_E) and the rating of perceived exertion (RPE) for crawling and walking. Results indicated that HR, $VO_{2,}$ and V_E were all significantly (statistically and practically) higher when crawling compared to walking. Quantifying the physiological demands using different locomotive strategies during evacuation provides a means to evaluate human evacuation performance (e.g., how far are evacuees able to travel during emergency situations). Accordingly, a second purpose of this study was to investigate the effects of different locomotive postures on physiological demands.

2. Methodology

2.1. Subjects

Twenty-four (24) subjects (12M/12F) were recruited from the Auburn University, Alabama community. All subjects were free of documented musculoskeletal injuries and cardiovascular diseases. Subject (M/F) data included [mean (SD)]: age-years [25.67 (2.02)/24.5 (1.73)]; height-cm [177.75 (2.96)/164.33 (2.53)]; weight-kg [76.5 (3.12)/56.25 (3.91)]; and BMI [24.21 (0.6)/20.81 (1.03)]. The study was approved by the Auburn University Institutional Review Board (IRB) and all subjects provided written informed consent.

2.2. Equipment

A 91.44 m (slightly curved) concrete test track was established using safety cones and barriers, on the third floor concourse of the Auburn University Coliseum. The test track was marked every 9.14 m to detect potential velocity changes. The start and finish lines were set 3.05 m from the beginning and the end of the track to control for any acceleration or deceleration effects. A digital video camera (Canon FS300) was mounted on a wheeled cart which followed subjects to record their movement. A COSMED K4b2 (COSMED, Rome, Italy) was used to measure VO_2, $V_{E,}$ and respiratory exchange ratio (RER). The COSMED K4b2 is a wireless, portable metabolic cart that allows accurate measurement of VO_2, $V_{E,}$ and RER (Duffield et al., 2004; McLaughlin et al., 2001). It is light-weight (~2.3 kg) and may be easily transported and operated. A Garmin Forerunner 110 (Garmin International, Inc., Olathe, Kansas) was used to continuously measure HR. The Garmin Forerunner 110 provides one of the easiest and most accurate methods to track continuous heart rate in beats per minute. Subjects were required to wear knee pads, elbow pads, and gloves while performing the crawling activities.

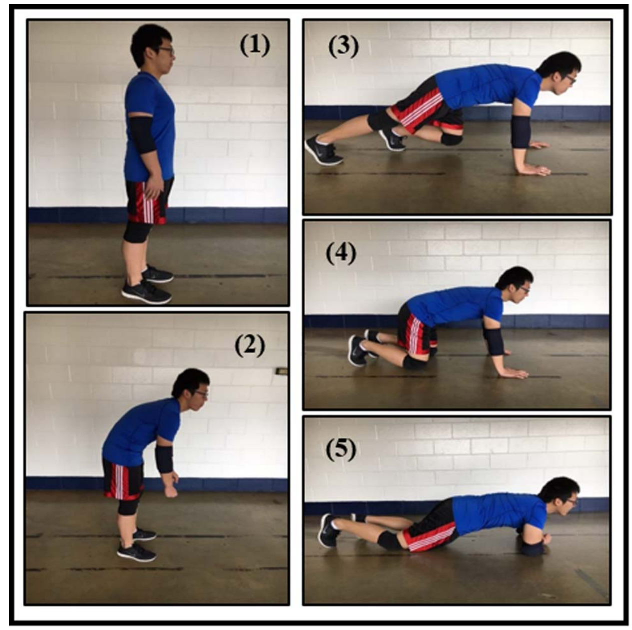

Fig. 1. Evacuation postures.

2.3. Procedure

After providing informed consent, each subject's age, gender, height and weight were recorded. Subjects were then instrumented with a COSMED K4b2 unit and a HR monitor. The COSMED K4b2 was calibrated (room air, reference gas, turbine, and gas delay) prior to each test. Subject resting VO_2 and resting heart rate (HR_{rest}) were recorded before starting each trial. Each subject participated in five separate trials (up to 91.44 m each) using five different postures including: (1) Upright Walking (UW), (2) Stoop-Walking (SW), (3) Foot and Hand Crawling (FHC), (4) Knee and Hand Crawling (KHC) and (5) Low Crawling (LC) (Fig. 1). The five postures were assigned in randomized order to negate potential order effects (i.e., learning and fatigue). Subjects were provided an opportunity to familiarize themselves with the study postures and equipment through completion of a 10-min pre-experiment practice session. Participants were instructed to be well rested, well hydrated, and caffeine free for at least 3 h prior to the experiment. Subjects were instructed that all trials were simulating an evacuation scenario and that they should complete the trials as rapidly as possible while maintaining the tested postures.

The test track was 91.44 m in length and divided into ten (10), 9.14 m segments (Fig. 2). Subject travel time to pass each marked-segment and segmental velocity was determined by reviewing the video recordings captured during each trial. The reference for passing time was when each subject's entire body passed the line of each segment. For the stooped walking posture, subjects were instructed to stoop down while keeping a tennis ball attached to a handheld stick in contact with the ground approximately 0.6 m directly in front of them. Subjects were instructed to maintain this posture during the entirety of the stoop walking trial.

During the experiment, an investigator closely followed each subject while pushing a cart with a digital video camera mounted to record each trial (Fig. 3). Subjects were asked to report their 'whole body' rating of perceived exertion (RPE) using Borg's perceived exertion scale (0–10) (Borg, 1998) after each trial. Recorded videos were used to determine intermediate times and velocities, as subjects passed over