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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.

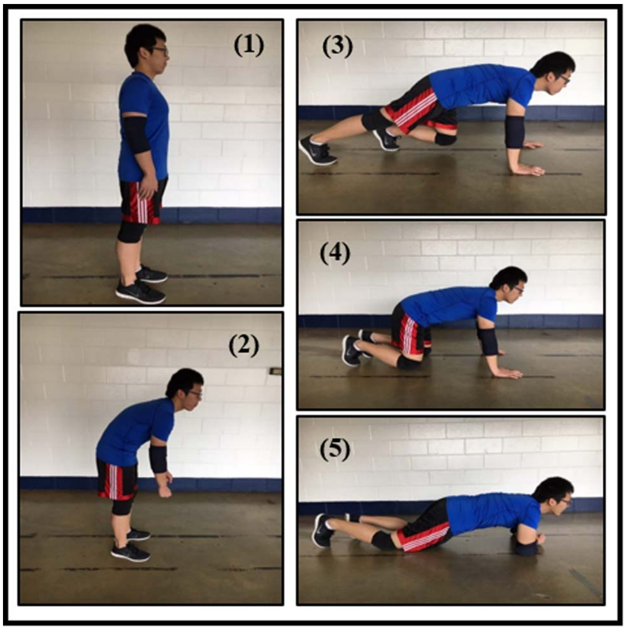

Fig. 1. Evacuation postures.

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

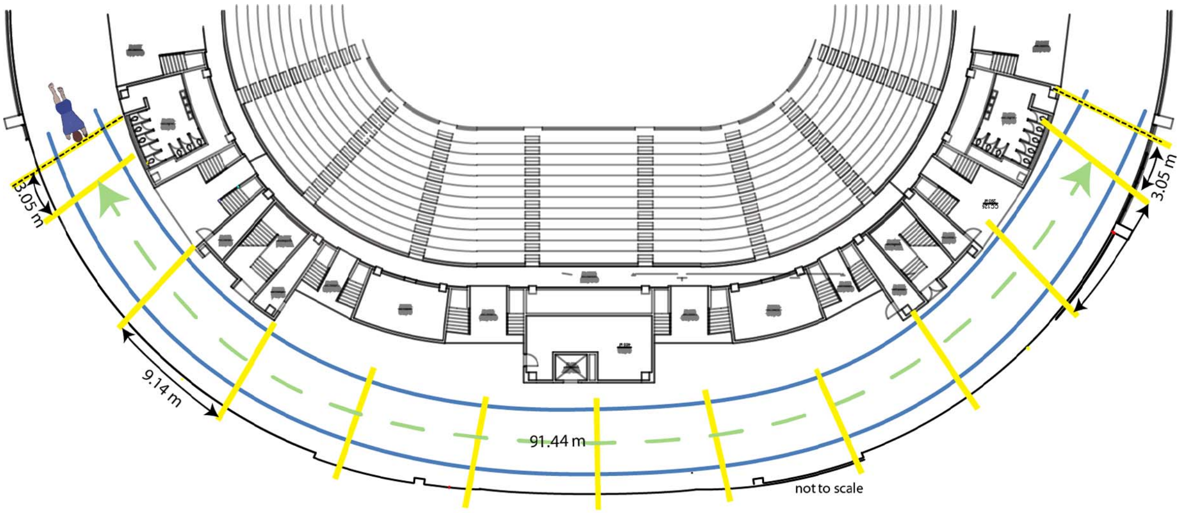

Fig. 2. Test track.

each track section. During each trial, subjects had the ability to stop and/or request rest at any time. Subjects were provided sufficient rest to ensure that their post-trial resting HR returned to within 10% of their initial HR_{rest} between successive trials. All subjects performed the test individually on the same day and no subject saw others performing the test. Total experiment time for each subject was approximately 2.5 h including the time to put on experimental instruments (heart rate monitor and portable metabolic system). Stopping criteria (Dwyer and Davis, 2005) for the trials were: Onset of angina or angina-like symptoms; signs of poor perfusion: light-headedness, confusion, ataxia, pallor, cyanosis, nausea, or cold and clammy skin; physical or verbal manifestations of severe fatigue; injury; test equipment failure; reaching 85% of subject age-adjusted HR_{max} (220-age); or a trial termination request by the subject.

3. Statistical analysis

Statistical hypotheses were developed to determine differences in ‘Velocity’ (m/s), ‘Distance’ (m), ‘Heart Rate’ (bpm), ‘Volume of Oxygen Consumption’ ($mL/(kg{\cdot}min^{-1})$), ‘Ventilation Rate’ (L/min), ‘Respiratory Exchange Ratio’, and ‘Rating of Perceived Exertion’ among the two walking (UW, SW) and three crawling (KHC, FHC, LC) postures. Independent variables included the five postures and gender. Dependent variables were time, distance, VO_2, V_E, RER, HR, and RPE. Potential differences in velocity, VO_2, V_E, RER, HR and RPE across the different postures were analyzed using analysis of variance (ANOVA). Post-hoc tests were performed using Tukey’s Honestly Significant Difference (HSD).

In this study, travel distances for different postures were treated as censored data (subjects’ maximum travel distances were partially known). Travel distance was analyzed using survival analysis with the Kaplan-Meier estimator (Kaplan and Meier, 1958). Multivariate survival analyses were conducted using the Cox Proportional Hazards method (Cox, 1972). Cox Proportional Hazards Method is the appropriate way to treat censored data. It is used to investigate the effect of different variables upon the time a specified event takes to occur. In this study, the event for the Cox Proportional Hazards Model was defined as when the subjects’ stopped the trial. Type I error rates were set at 0.05 for all statistical tests.

4. Results

All twenty-four (24) subjects completed the 91.44 m UW and SW trials. The average completion times for UW and SW were 49.75 ± 11.05 and 52.38 ± 11.52 s, respectively. As expected, postures affected completion distance. Only one (1) male subject completed all three 91.44 m crawling (FHC, KHC, LC) trials. Table 1 summarizes the number of completions (# of males/# of females) and

Fig. 3. Digital camera to record the entire trial.

Table 1
Completed trials and average travel distances for different postures.

	UW	SW	FHC	KHC	LC
Completed the trial	24 (12 M/12F)	24 (12 M/12F)	1 (1M/0F)	2 (2M/0F)	1 (1M/0F)
Gave up voluntarily	0 (0M/0F)	0 (0M/0F)	12 (7M/5F)	10 (7M/3F)	9 (6M/3F)
Reached 85% age-adjusted HR_{max}	0 (0M/0F)	0 (0M/0F)	11 (4M/7F)	12 (3M/9F)	14 (5M/9F)
Reached 70% age-adjusted $HR_{reserve}$	0 (0M/0F)	0 (0M/0F)	14 (6M/8F)	14 (5M/9F)	14 (5M/9F)
Average travel distance (m)	91.44	91.44	45.784 ± 19.06	55.75 ± 19.51	52.60 ± 17.22

Table 2
Results of Cox Proportional Hazards Regression Analysis.

Parameter	Parameter estimate	Chi-square	p	Hazard ratio (95% CI)
Gender, female	2.83	45.25	< 0.001	16.95 (7.43, 38.67)
Posture, FHC	0.61	4.03	0.04	1.84 (1.02, 3.34)
Posture, KHC	−0.24	0.64	0.43	0.79 (0.44, 1.42)

average travel distances for different postures. Reasons for not completing the entire 91.44 m crawling trial in this study were voluntarily giving up or reaching 85% of subject-specific age-predicted maximum HR (220-age). Survival analysis indicated that only 4.17%, 8.33% and 16.67% of participants completed the 76.2 m distance to an exit for a building enforced by the ICC for FHC, LC and KHC, respectively (Fig. 4).

Multivariate survival analyses using the Cox Proportional Hazards method (Table 2) indicated that the FHC completion rate per unit distance was significantly lower than LC ($p = .044$, Hazard Ratio = 1.841). No significant difference was detected between KHC and LC ($p = .425$). Additionally, gender demonstrated a significant decrease in trial completion distance ($p < .001$). Completion rate per unit distance for females was significantly lower than the completion rate for males ($p < .001$, Hazard Ratio = 16.95). Average crawling completion distances (FHC, KHC, LC) for male subjects were more than 60.96 m, while average crawling completion distances for female subjects were less than 45.72 m (Fig. 5).

Results demonstrated that different postures affected velocities ($F_{4,88} = 132.71$, $p < .001$). Walking was much faster than crawling. Average UW speed in this study was measured at 1.93 ± 0.43 m/s and average SW speed was measured at 1.84 ± 0.45 m/s. Velocities for all three types of crawling were less than 1.22 m/s. Gender exhibited a significant effect on travel velocity (Fig. 6). Males moved faster than females in UW ($F_{1,22} = 52.87$, $p < .001$), SW ($F_{1,22} = 17.70$, $p < .001$), FHC ($F_{1,22} = 53.68$, $p < .001$), KHC ($F_{1,22} = 57.59$, $p < .001$) and LC ($F_{1,22} = 43.66$, $p < .001$). Post-hoc Tukey HSD tests showed that FHC speed was significantly faster than KHC ($p < .05$) and LC ($p < .05$). KHC was significantly faster than LC ($p < .05$). Average FHC speed was measured at 1.20 ± 0.29 m/s. A post hoc Tukey HSD test also indicated that there was no significant difference between UW and SW ($p > .05$).

Velocities for all crawling postures decreased significantly after the first 9.14 m of travel. Fig. 7 shows the average track segmental velocities for different postures. Lines in the graph represent the track segmental velocity and columns represent the number of subjects that passed each segment.

Over the entire study, the average time that subjects were willing and capable of crawling was less than 1 min. Results indicated that postures had a significant effect on physiological demands. Average heart rate (HR_{avg}) was significantly affected by posture ($F_{4,88} = 115.41$, $p < .001$). During UW and SW, subject's HR increased slightly as walking commenced and never achieved 70% of their age-adjusted HR_{max}. Conversely, in the three crawling trials, HR, VO_2, V_E and RER dramatically increased soon after initiation of crawling. All subjects reached 70% of their age-adjusted HR_{max} during the crawling trials. Most subjects reached 70% of age-adjusted HR_{max} between 25 s and 40 s of crawling (Fig. 8). The American College of Sports Medicine (ACSM) (2007) states: "During low-intensity physical activities, HR will be below 50% of HR_{max}; during moderate-intensity physical activity, HR will be around 50–70% of HR_{max}; and during high-intensity physical activity, HR will be around 70–85% of HR_{max}." In this study, the test was stopped immediately if the subject reached 85% of his/her age-adjusted HR_{max}. ACSM has defined two stopping criteria for submaximal tests. The first criterion is if subjects' HR reaches 85% of their age-adjusted HR_{max}. The second criterion is if subjects reach 70% of their age-adjusted heart rate reserve ($HR_{reserve}$) (Dwyer and Davis, 2005). The average 70% of age-adjusted $HR_{reserve}$ was calculated at 161.35 ± 3.01 bpm, which was slightly lower than 85% of age-adjusted HR_{max} (165.68 ± 1.64 bpm). Table 1 includes the number of

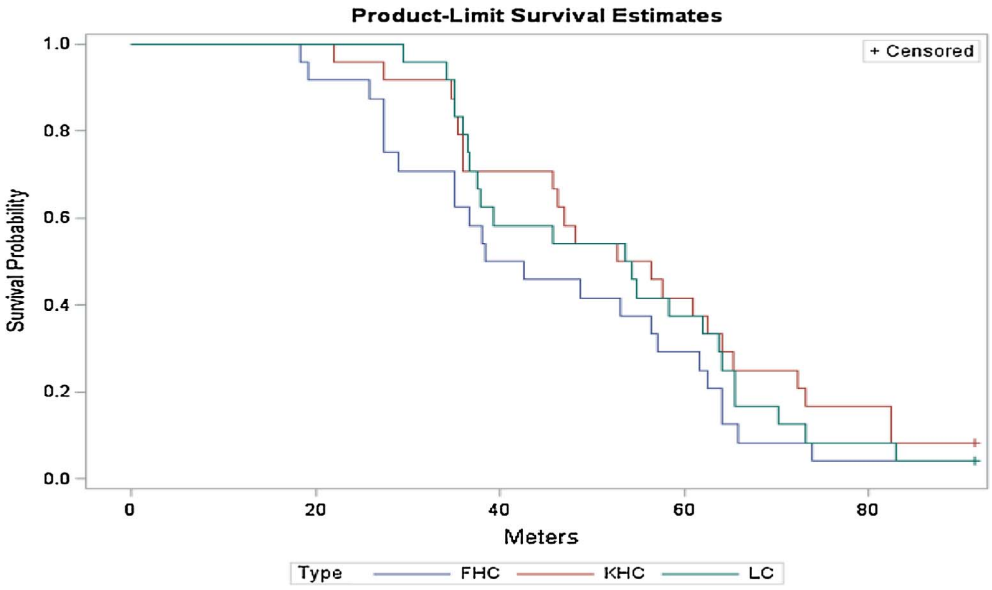

Fig. 4. Survival curve (completion rate) for crawling postures.

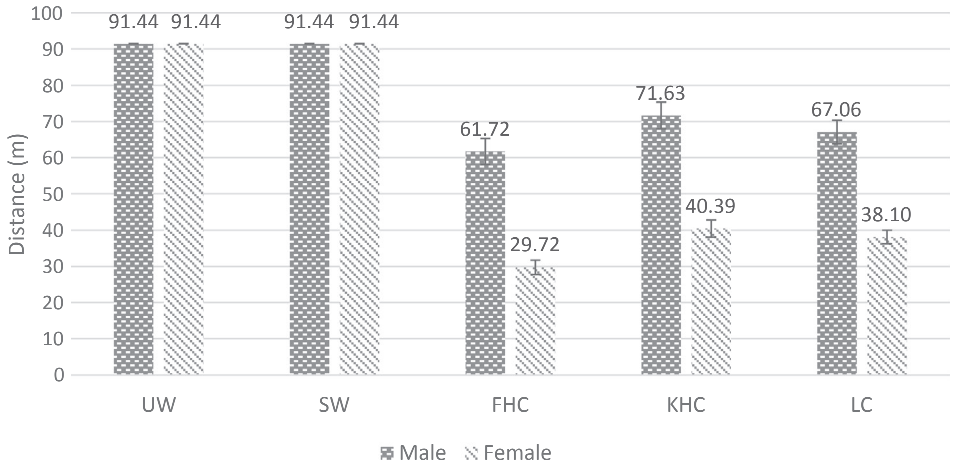

Fig. 5. Average travel distances for different postures.

subjects that reached 85% of their age-adjusted HR_{max} and the number of subjects that reached 70% of their age-adjusted $HR_{reserve}$. Fig. 8 is an example of a single subject's HR responses in different postures. This subject's 70% age-adjusted $HR_{reserve}$ (162 bpm) and 85% age-adjusted HR_{max} (168.3 bpm) are indicated in the figure.

Fig. 9 shows HR_{avg} by time based on the remaining subjects. A post hoc Tukey HSD test indicated that HR_{avg} during FHC was significantly higher than HR_{avg} during KHC ($p < .05$) and LC ($p < .05$). HR_{avg} during KHC and LC were not significantly different ($p > .05$). HR_{avg} for UW and SW in this study were 92 bpm and 93 bpm, respectively, while HR_{avg} for FHC, KHC and LC were 134 bpm, 128 bpm and 130 bpm, respectively.

Posture also significantly affected the time that subjects required to return to their resting HR ($F_{4,88} = 93.54$, $p < .001$). It took a substantially longer time (seconds) for subjects to return to their HR_{rest} after crawling [KHC (3 8 6), LC (4 1 5), FHC (5 5 6)] compared to walking [UW (73), SW (1 1 5)]. A post hoc Tukey HSD test showed that time to return to HR_{rest} after FHC was significantly longer than the time to return to HR_{rest} after KHC ($p < .05$) and LC ($p < .05$). On average, it took subjects 9 min and 16 s to return to their HR_{rest} after FHC. No significant difference was detected between KHC and LC ($p > .05$). Figs. 10 and 11 show VO_2 and V_E during different types of locomotion. The average VO_2 and V_E for each time point in Figs. 10 and 11 were based on the remaining subjects. Posture significantly affected VO_2 ($F_{4,88} = 89.1$, $p < .001$) and V_E ($F_{4,88} = 103.5$, $p < .001$). VO_2 was significantly higher during crawling than during walking ($p < .05$), with V_E exhibiting a similar trend. On average, V_E during the FHC trials was 51.12 L/min higher than the UW trials. VO_2 during FHC was 28.10 mL/(kg·min^{-1}) higher than during the UW trials. However, a statistically significant gender effect on VO_2 and V_E was not detected.

RER is the ratio of the volume of carbon dioxide production to the volume of oxygen consumption (VCO_2/VO_2). Average RER for FHC, KHC and LC in this study was measured at 1.09 ± 0.09, 1.05 ± 0.10 and 1.06 ± 0.05, respectively. Average RER during walking trials was measured lower than 0.9. According to ACSM (2007) for resting conditions, a person's RER is around 0.8, whereas a RER higher than 1.0, suggests a high intensity level exercise. During the FHC trials, 15 out of 24 subjects' RER reached 1.2. Results also indicated that gender did not show a significant effect on RER during crawling trials. Ratings of Perceived Exertion (RPE) (0–10) also displayed a much higher response during crawling [KHC (6.29), LC (7.08), FHC (8.13)] in comparison to the walking trials [UW (0.83), SW (2.50)].

Locomotive postures also significantly affected the amount of time that subjects required to return to their Resting Heart Rate (HR_{rest}) ($F_{4,88} = 93.54$, $p < .001$). It took significantly longer for subjects to return to their Resting Heart Rate (HR_{rest}) after crawling compared to walking (Fig. 12).

5. Discussion

This study demonstrated clear performance decrements associated with the adoption of crawling postures, the recommended method for exiting burning structures during a severe fire emergency. Most notably, only one male subject of the 24 healthy, approximately college-aged males and females who participated in this study completed all three 91.44 m crawling (FHC, LC, KHC) trials. Moreover, only 4.17%, 8.33% and 16.67% of participants were able to crawl the 76.2 m distance to an exit for a building (sprinkler system is in place) enforced by

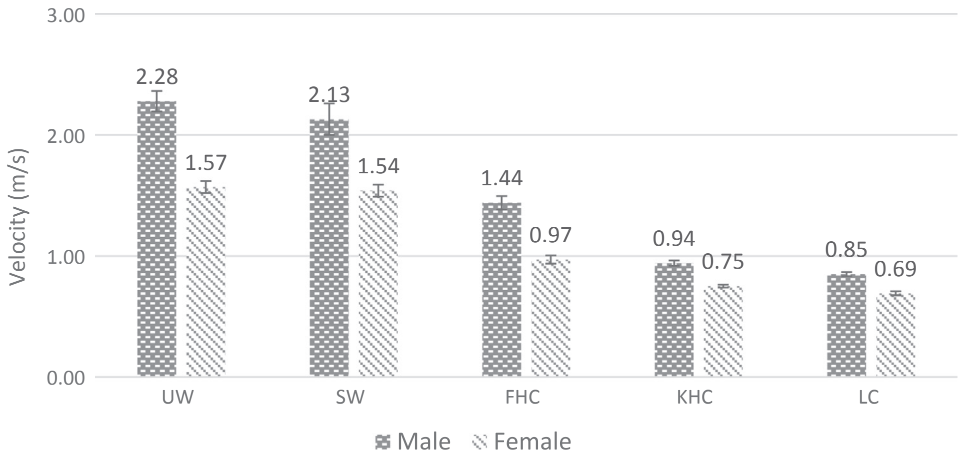

Fig. 6. Average travel velocities for different postures.

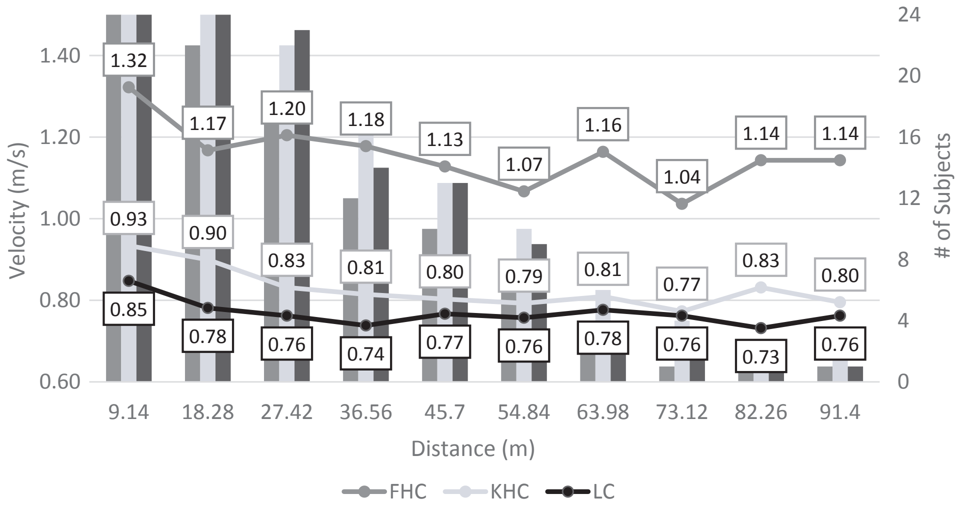

Fig. 7. Velocities and number of completions by track segment.

the ICC during FHC, KHC and LC before being forced to stop (by the researcher per IRB restriction) due to reaching 85% of their age-adjusted HR_{max}. These findings suggest that current ICC (2015) standards that enforce a maximum distance to an exit for a building may be too great for even healthy individuals. When considering the rapidly expanding number of elderly and obese individuals and the physiological decrements already affecting those populations (Ogden et al., 2015; He et al., 2016), it is imperative that further research investigate evacuation routes for emergency situations.

Average UW velocity (1.93 m/s) measured in this study was faster than normal walking velocities, but very similar to the maximum walking velocities measured in previous studies (Bohannon, 1997; Browning et al., 2006; Knoblauch et al., 1996). Average KHC speed was measured at (0.84 m/s) which was like the four-point crawling speed measured by in several crawling evacuation studies (Muhdi et al., 2006; Kady and Davis, 2009a,b). Velocities during UW and SW were approximately twice as fast as crawling in this study. Of the three crawling postures, FHC has the advantage of higher speed compared to the other two, but the FHC completion distance was significantly shorter than KHC and LC. It can be clearly understood by these results that a reduction in breathing zone height due to smoke during a fire emergency may create potentially dire consequences for an evacuee for several reasons. Not only is the smoke a threat to the lungs and vision of the evacuee, the reduced ceiling height due to the smoke slows the escape and shortens achievable evacuation distance. The reduction in velocity and travel distance while crawling makes it more difficult to successfully evacuate.

The reasons why differences exist in velocity and travel distance among the crawling postures cannot be explained by this study. No learning effect on travel velocity was detected in this study. Fatigue during crawling, characterized by a decrease in segmental travel velocity and an increase in physiological demand was observed after 9.14 m of travel in this study. Participants did not experience fatigue during UW and SW. During UW and SW, most participants maintained their velocity throughout the entire travel. One potential explanation for participants experiencing fatigue during crawling but not walking is that a greater number of muscle are required for crawling than for walking. However, muscle activity was not measured in the current study. Further study in analyzing muscle activation levels and patterns during crawling and walking is needed to clarify the reason why crawling causes fatigue more frequently than walking.

Unlike previous studies which only investigated KHC and UW, this study reports physiological demands for three different crawling postures (FHC, KHC, LC) and two walking postures (UW and SW) representing different potential breathing zone heights during evacuation. All dependent variables (HR, VO_2, V_E, RER and RPE) in this study were significantly different between postures. Crawling was more physically demanding than walking, represented by higher: HR_{avg}, VO_2, V_E, and RER. Physiological demands of UW and KHC found in this study were similar to those reported in previous crawling studies (Morrissey

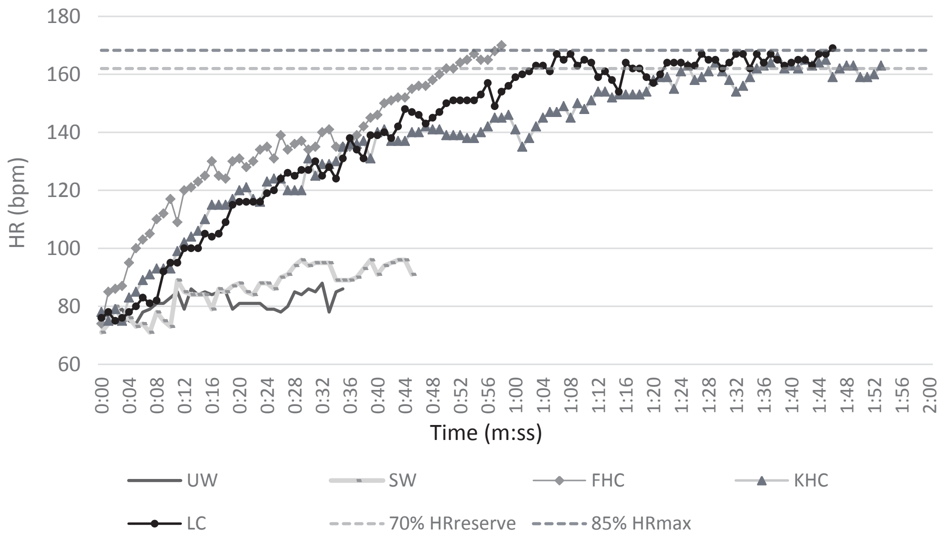

Fig. 8. Single subject heart rate response.

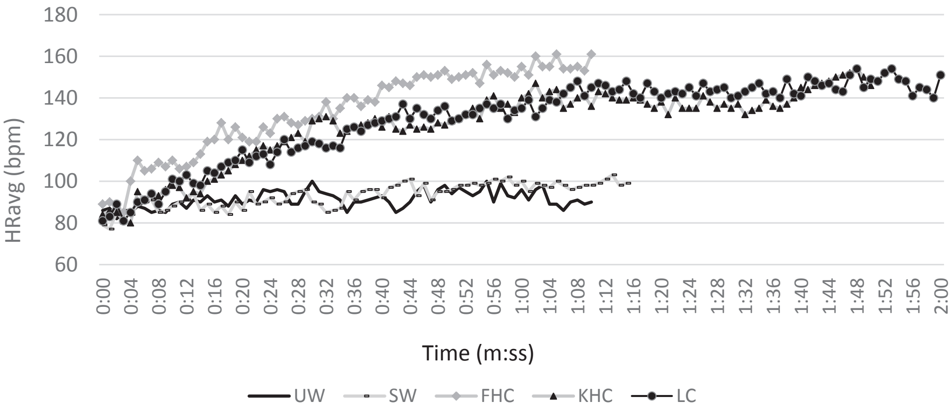

Fig. 9. Average heart rates (HR_{avg}).

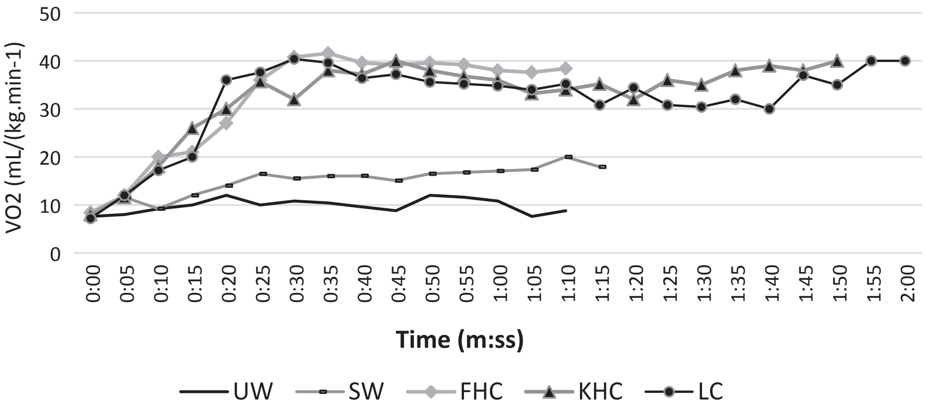

Fig. 10. Average volumes of oxygen consumption (VO_2).

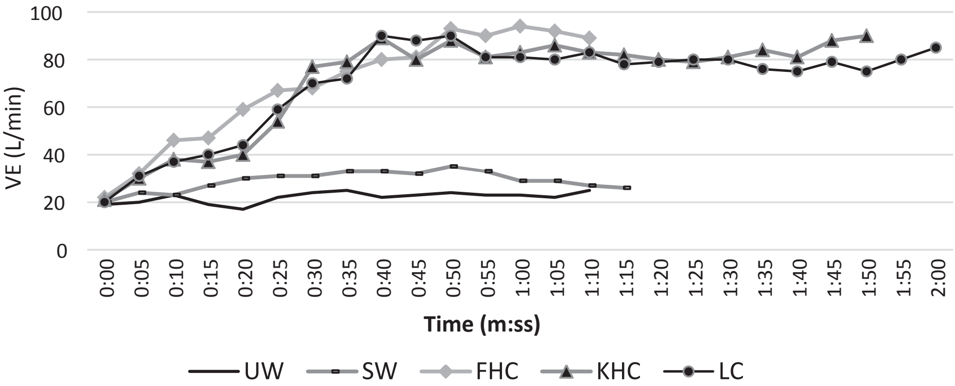

Fig. 11. Average ventilation rates (V_E).

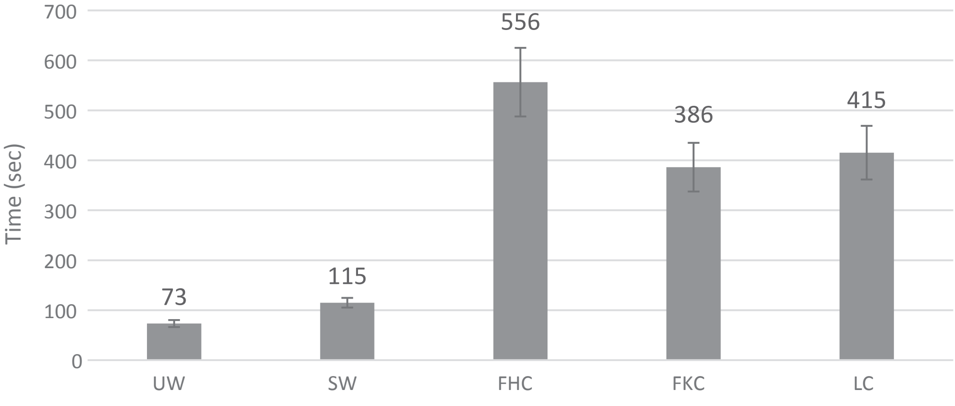

Fig. 12. Time to return to resting heart rate (HR_{rest}).

et al., 1985; Gallagher et al., 2011; Davis, 2011). HR_{avg} for crawling was approximately 71% higher than walking, and the average VO_2 for crawling was approximately 87% higher than walking. For all three crawling (FHC, KHC and LC) tasks, individual HR and VO_2 dramatically increased after crawling for approximately 20 s. All subjects reached 70% age-adjusted HR_{max} during crawling and 14 of 24 subjects were forced to stop after reaching 85% of their age-adjusted HR_{max}. However, in the UW and SW trials, no subject reached 70% age-adjusted HR_{max}. Heart rate responses recorded in this study indicates that crawling is a high-intensity activity. As expected, V_E exhibited a similar pattern to HR and VO_2 in this study.

Previous research indicated that RER increased with exercise intensity. RER is typically around 0.8 at rest and can exceed 1.0 during intense exercise. A high RER indicates that carbohydrates are being predominantly used, whereas a low RER suggests lipid oxidation (Simonson and DeFronzo, 1990). Average RER for FHC, KHC and LC in this study are larger than 1.0 and very close to 1.1, implying crawling is a very physically demanding method of locomotion.

Atypical postures (stoop-walking and crawling) are frequently used by emergency responders (e.g., firefighters), in deteriorating environments such as severe fire conditions. Several previous studies examined firefighters' physiological demands when performing firefighting or rescuing (Barnard and Duncan, 1975; Sothmann et al., 1990; Davis and Gallagher, 2014; Davis et al., 2014). Sothmann et al. (1990), studied twenty (20) firefighters while monitoring HR, VO_2, and V_E during crawling rescue tasks and found that the subject group had an average VO_2 of 39.9 mL/(kg·min), an average V_E of 46.7 L/min, and an average HR of 173 bpm. A more recent study by Davis and Gallagher (2014) examined the physiological demands of crawling for fourteen (14) firefighter trainees. Those firefighter trainees were performing crawling search exercises with durations ranging between 14.4 and 21.0 min. They found that the HR_{max} during crawling averaged 174 bpm, about 97 bpm higher than their resting HR. The volume of air consumed from the SCBA's averaged 52.9 L/min. The other firefighter trainee study by Davis, et al., (2014) had a very similar pattern in physiological demands for crawling activities. Physiological demands during crawling measured in the present study are similar to previous firefighting research. Finally, crawling was perceived to be much more difficult than walking in this study. All subjects rated FHC as the most difficult to perform among all five postures as evidenced by RPE.

There were several limitations to this study. First, the recruited subjects were college students ('normal' Body Mass Index (BMI): 18.5–24.9 and aged between 19 and 30). No consideration was given to other age groups or BMI groups. Physiological measurements may have been substantially different had alternative age groups or subjects with higher BMIs participated. Second, subjects were instrumented with a COSMED K4b2 unit (~2.3 kg in total) and a face mask to record their respiratory responses. The COSMED K4b2 unit and respiratory face mask may affect natural behaviors (i.e., increased discomfort, potential vision degradation, etc.). Third, all experimental trials were conducted in a controlled environment (normal, room-temperature, smooth dry flat surface, and fairly straight track (slightly curved, no turns) conditions). In real evacuation scenarios, performance may be affected by factors such as obstacles, thermal stress, limited visibility, solo/group evacuation, and varying building geometries, among others. A recent study by Dias et al., (2014) reported the impact of solo and collective bipedal movement through various turning angles (Dias et al., 2014). Fourth, subjects wore protective padding to avoid injury which is not representative of real evacuation scenarios). Finally, crawling trials were immediately stopped if subjects reached their 85% age-predicted maximum heart rate. While this safety measure is necessary in a research environment, reaching 85% age-predicted maximum heart rate may not accurately represent a subjects' maximum crawling distance in a life threatening environment.

6. Conclusions

Findings from this study suggest that a reduction in breathing zone height due to smoke or toxic gases creates potentially dire consequences for an evacuee for several reasons. Not only is the smoke a threat to the lungs and vision of the evacuee, the reduced ceiling height due to the smoke slows the escape and shortens achievable evacuation distance. The reduction in velocity and travel distance while crawling makes it more difficult to successfully evacuate.

The following conclusions may be drawn from the current study:

(1) Crawling is significantly slower than walking. Crawling velocities decrease significantly as travel distance increases. The average maximum crawling distance is less than 76.2 m.
(2) Gender has a significant effect on crawling velocity and maximum crawling distance. Males move faster and attain longer distances than females in all crawling postures.
(3) Crawling is more physically demanding than walking, evidenced by higher HR_{avg}, higher VO_2, higher V_E, and higher RERs, each dramatically increasing after crawling for approximately 20 s.
(4) Crawling is an intense activity ($RER > 1.0$) that takes subjects more time to recover compared to walking, and is perceived to be more physically demanding than walking on an identical course.
(5) Gender has no significant effect on HR, VO_2, V_E, and RER during crawling.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ssci.2017.12.032.

References

American College of Sports Medicine, 2007. ACSM's Metabolic Calculations Handbook. American College of Sports Medicine.
Barnard, R., Duncan, H., 1975. Heart rate and ECG responses of firefighters. J. Occup. Med. 17, 247–250.
Bohannon, R., 1997. Comfortable and maximum walking speed of adults aged 20–79 years: reference values and determinants. Age Ageing 26 (1997), 15–19.
Borg, G., 1998. 1998Borg's Perceived Exertion and Pain Scales. Human Kinetics.
Browning, R., Baker, E., Herron, J., Kram, R., 2006. Effects of obesity and sex on the energetic costs and preferred speed of walking. J. Appl. Physiol. 100 (2006), 390–398.
Cao, L., Davis, J., Gallagher, S., 2014. The impact of posture on evacuation speed. In: Proceedings of the 2nd International Tall Building Fire Safety Conference, pp. 111–121. ISBN 978-1-904521-85-3.
Cox, D., 1972. Regression models and life-tables. J. Roy. Stat. Soc. 34 (1972), 187–220.
Davis, J., Gallagher, S., 2014. Physiological demand on firefighters crawling during a search exercise. Int. J. Ind. Ergon. 44 (2014), 821–826.
Davis, J., Tang, R., Sesek, R., Gallagher, S., 2014. Evaluating firefighter crawling performance in a controlled environment. Advances in Safety Management and Human Factors. 2014, 3–9.
Davis, R., 2011. A Comparison of Physiological Effects of Traditional Walking Locomotion to Crawling. Thesis, East Stroudsburg University of Pennsylvania.
Dias, C., Ejtemai, O., Sarvi, M., Shiwakoti, N., 2014. Pedestrian walking characteristics through angled corridors: an experimental study. Transport. Res. Rec.: J. Transport. Res. Board 2421, 41–50.
Dill, D., 1965. Oxygen used in horizontal and grade walking and running on the treadmill. J. Appl. Physiol. 20 (1965), 19–22.
Duffield, R., Dawson, B., Pinnington, H., Wong, P., 2004. Accuracy and reliability of a Cosmed K4b 2 portable gas analysis system. J. Sci. Med. Sport 7 (1), 11–22.
Dwyer, G., Davis, S., 2005. ACSM's Health-Related Physical Fitness Assessment Manual. Lippincott, Williams & Wilkins. ISBN-10: 1451115687.
Flynn, T., Connery, S., Smutok, M., Zeballos, R., Weisman, I., 1994. Comparison of

cardiopulmonary responses to forward and backward walking and running. Med. Sci. Sports Exerc. 26 (1994), 89–94.

Francis, K., Hoobler, T., 1986. Changes in oxygen consumption associated with treadmill walking and running with light hand-carried weights. Ergonomics 29 (1986), 999–1004.

Fudge, B., Wilson, J., Easton, C., Irwin, L., Clark, J., Haddow, O., Kayser, B., Pitsiladis, Y., 2007. Estimation of oxygen uptake during fast running using accelerometry and heart rate. Med. Sci. Sports Exerc. 39 (2007), 192–198.

Gallagher, S., Pollard, J., Porter, W., 2011. Locomotion in restricted space: kinematic and electromyographic analysis of stooped-walking and crawling. Gait Posture 33 (2011), 71–76.

He, W., Goodkind, D., Kowal, P., 2016. An Aging World: 2015 – International Population Reports. U.S Census Bureau.

International Code Council (ICC), 2015. International Building Code. International Code Council, 2015. ISBN-10: 1609834682.

Jones, B., Toner, M., Daniels, W., Knapik, J., 1984. The energy cost and heart-rate response of trained and untrained subjects walking and running in shoes and boots. Ergonomics 27 (1984), 895–902.

Kady, R., Davis, J., 2009a. The effect of occupant characteristics on crawling speed in evacuation. Fire Saf. J. 44 (2009), 451–457.

Kady, R., Davis, J., 2009b. The impact of exit route designs on evacuation time for crawling occupants. J. Fire Sci. 27 (2009), 481–493.

Kaplan, E., Meier, P., 1958. Nonparametric estimation from incomplete observations. J. Am. Stat. Assoc. 53 (1958), 457–481.

Knoblauch, R., Pietrucha, M., Nitzburg, M., 1996. Field studies of pedestrian walking speed and start-up time. J. Transport. Res. Board 1538, 1996.

Martin, P., Rothstein, D., Larish, D., 1992. Effects of age and physical activity status on the speed-aerobic demand relationship of walking. J. Appl. Physiol. 73 (1992), 200–206.

Mattsson, E., Larsson, U., Rössner, S., 1997. Is walking for exercise too exhausting for obese women? Int. J. Obes. Rel. Metab. Dis. 21, 380–386.

McLaughlin, J., King, G., Howley, E., Bassett Jr, D., Ainsworth, B., 2001. Validation of the COSMED K4b2 portable metabolic system. Int. J. Sports Med. 22 (04), 280–284.

Morrissey, S., George, C., Ayoub, M., 1985. Metabolic costs of stoopwalking and crawling. Appl. Ergon. 16 (1985), 99–102.

Moss, K., 1934. The energy output of coal miners during work. Trans. Am. Inst. Min. Metall. Eng. 189, 132–149.

Muhdi, R., Davis, J., Blackburn, T., 2006. Improving occupant characteristics in performance-based evacuation modeling. In: Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting, vol. 50, pp. 1199–1203.

Nagai, R., Fukamachi, M., Nagatani, T., 2006. Evacuation of crawlers and walkers from corridor through an exit. Physica A 367 (2006), 449–460.

National Fire Protection Association, 2015. 2015 NFPA 101: Life Safety Code. The National Fire Protection Association. ISBN-10: 1455909025.

Occupational Safety and Health Administration (OSHA), 2015. Occupational Safety and Health Administration (OSHA) – Elaws – Employment Laws Assistance for Workers and Small Businesses. Retrieved from < https://webapps.dol.gov/elaws/osha/lead/glossary.asp > .

Ogden, C., Carroll, M., Fryar, C., Flegal, K, 2015. Prevalence of Obesity Among Adults and Youth: United States, 2011–2014. U.S. Department of Health and Human Services.

Simonson, D., DeFronzo, R., 1990. Indirect calorimetry: methodological and interpretative problems. Am. J. Physiol. 258 (1990), 399–412.

Sothmann, M., Saupe, K., Jasenof, D., Blaney, J., Fuhrman, S., Woulfe, T., Raven, P., Pawelczyk, J., Dotson, C., Landy, F., Smith, J., Davis, O., 1990. Advancing age and the cardiorespiratory stress of fire suppression: determining a minimum standard for aerobic fitness. Hum. Perform. 3 (1990), 217–236.