# Evaluation of Evacuation Performance Using Different Locomotive Postures

by

Li Cao

A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
August 5, 2017

Keywords: Emergency Evacuation, Physiological Demands, Xsens



Approved by

Jerry Davis, Chair, Professor of Industrial and Systems Engineering
Sean Gallagher, Associate Professor of Industrial and Systems Engineering
Richard Sesek, Associate Professor of Industrial and Systems Engineering
Mark Schall, Assistant Professor of Industrial and Systems Engineering

Abstract

Humans may adopt atypical locomotive postures due to breathing zone constraints during emergency evacuations. Except for walking upright, postures during evacuation have been sparsely researched. This study evaluated travel velocity and physiological demand for five different evacuation postures (Upright Walking (UW), Stoop-Walking (SW), Foot and Hand Crawling (FHC), Knee and Hand Crawling (KHC) and Low Crawling (LC)) representing different breathing zone levels. Kinematic analysis of these different locomotive postures was also conducted using a 3D motion tracking system: Xsens.

Results indicate that locomotive posture impacts human velocity and physiological demands. Crawling is significantly slower and more physically demanding (higher average Heart Rate (HRavg) level, higher Volume of Oxygen consumption ($VO_2$), higher Ventilation Rate ($V_E$), and higher Respiratory Exchange Ratio (RER)) than walking. Average maximum crawling distance is less than 250 feet (76.2 m). Furthermore, Foot and Hand Crawling (FHC) is faster, but perceived to be more physically demanding than both Knee and Hand Crawling (KHC) and Low Crawling (LC). 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.

Results of the study can provide a way to evaluate human capabilities and limitations during evacuation and give additional guidance about the effects of different postures (breathing zone heights) on egress performance, which supports the design of building evacuation routes.

Acknowledgments

I wish to express my gratitude to my committee chair, Dr. Jerry Davis, for his guidance, wisdom, inspiration, as well as confidence in me through this learning process. I truly admire his research skills which helped to make this work possible. My appreciation is also directed to Dr. Sean Gallagher, Dr. Richard Sesek, and Dr. Mark Schall for their responsiveness and support. I also give thanks to all my colleagues in the OSE/IP family. My sincere appreciation is extended to Dr. Ash Abebe, who provided me with excellent statistics support. My time in Auburn was one of the most memorable experiences in my entire life.

In addition, I would also like to thank the Deep South Center for Occupational Health and Safety, the National Institute for Occupational Safety and Health (NIOSH) for funding support.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

| | |
|---|---|
| ACSM | American College of Sports Medicine |
| BMI | Body Mass Index |
| bpm | beats per minute |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| EAP | Emergency Action Plan |
| ECG | Electrocardiogram |
| EMG | Electromyography |
| FHC | Foot and Hand Crawling |
| HR | Heart Rate |
| HRavg | Average Heart Rate |
| HRmax | Maximum Heart Rate |
| HRreserve | Heart Rate Reserve |
| HRrest | Resting Heart Rate |
| HSD | Honestly Significant Difference |
| IBC | International Building Code |
| ICC | International Code Council |
| ICP | Interlimb Coordination Patterns |

| | |
|---|---|
| IDLH | Immediately Dangerous to Life and Health |
| IPL | Ipsilateral Phase Lag |
| IRB | Institutional Review Board |
| KHC | Knee and Hand Crawling |
| LC | Low Crawling |
| MPH | Miles Per Hour |
| NFPA | National Fire Protection Association |
| NIOSH | The National Institute for Occupational Safety and Health |
| OSHA | Occupational Safety and Health Administration |
| PC | Points of Contact to the ground |
| PPE | Personal Protective Equipment |
| RER | Respiratory Exchange Ratio |
| RPE | Rating of Perceived Exertion |
| SCBA | Self-Contained Breathing Apparatus |
| SCT | Step Cycle Time |
| SL | Stride Length |
| SW | Stoop-Walking |
| TEEM | Total Energy Expenditure Measurement |
| UW | Upright Walking |
| $VCO_2$ | Volume of Carbon Dioxide production |
| $V_E$ | Ventilation Rate |
| $VO_2$ | Volume of Oxygen consumption |

# Chapter 1

## Introduction

The Occupational Safety and Health Administration (OSHA) has defined Immediately Dangerous to Life and Health (IDLH) as “an atmosphere that poses an immediate threat to life, would cause irreversible adverse health effects, or impair an individual's ability to escape from a dangerous atmosphere” [OSHA, 2015a]. According to the OSHA [2015a], to enhance safety, occupants in IDLH conditions are often required to wear specific Personal Protective Equipment (PPE) and protective respiratory equipment such as a Self-Contained Breathing Apparatus (SCBA), or to evacuate immediately.

The Emergency Action Plan (EAP) from OSHA [2015b] suggests that evacuations should be executed as quickly and safely as possible during an emergency. Questions that are frequently asked for emergency evacuations concerning evacuee safety include, “Can people successfully evacuate?” and “How fast should people be able to evacuate?” OSHA addresses such questions by establishing mandatory standards for evacuation and evacuation route design. OSHA [2015c] requires that workplaces must have at least two (2) exit routes to permit prompt evacuation of occupants during an emergency. However, OSHA does not specify the number of occupants, the size, or the layout of a workplace when more than two (2) exit routes are needed for successful evacuation. In addition, OSHA does not mandate, nor do they suggest guidance for evacuation time to indicate how fast people should evacuate.

Unlike OSHA, the International Building Code (IBC) from the International Code Council (ICC) and the National Fire Protection Association (NFPA) have more comprehensive standards for evacuation, including maximum building occupancy, number of exits, maximum travel distance to each exit, etc. [ICC, 2015; NFPA, 2015]. A majority of the IBC and NFPA standards were established based on opinions from a group of experts, limited experimental data, and controlled evacuation drills. Those experiments and drills were typically performed in optimal environmental conditions, which may not properly represent the real evacuation environment or evacuees' actual evacuation performance.

According to the NFPA [2015], most fire fatalities are not caused by direct burns, but by smoke inhalation. In fire conditions, smoke generated by incomplete burning contains hot and toxic chemicals, such as carbon monoxide, sulfur dioxide, nitrogen oxide, etc., which cause the lungs and the airway to become irritated, swollen, and blocked. The damaged airway and lungs then prevent oxygen from getting into the blood, which leads to respiratory failure. OSHA [2015d] has defined breathing zone as "… within a ten-inch radius of the worker's nose and mouth." In severe fire conditions, smoke, heat, and combustion gases rise and evacuees may be forced to lower their breathing zone to access cleaner and cooler air, which results in a change in locomotive posture and evacuation efficiency. In addition to breathable air, staying low also provides evacuees with clearer vision to recognize their surroundings and search for potential exit routes. Evacuees may also use atypical locomotion for accomplishing certain tasks, for example, crawling over obstacles, opening/closing a door, grabbing or using tools, etc. Therefore, both OSHA and NFPA suggest evacuees crawl low under smoke during severe fire evacuation [OSHA, 2017; NFPA, 2015].

Previous studies have demonstrated that environmental factors such as heat and smoke have a significant effect on human locomotive performance [Sander, Alexander, and Peter, 2011; Akizuki, Yamao, and Tanaka, 2007]. The deterioration of environmental conditions, in terms of heat, smoke, combustion gases, etc., could degrade vision and impede bipedal locomotion, significantly affecting evacuation performance.

There are relatively few studies focusing on adult crawling behaviors and most of those are not relevant to emergency evacuation. Interestingly, those limited studies overwhelmingly agree that crawling is a relatively slow and physically demanding method of locomotion compared to upright walking [Muhdi, Davis, and Blackburn, 2006; Gallagher, Pollard, and Porter, 2011; Morrissey, George, and Ayoub, 1985; Davis, 2011]. It is difficult to answer the questions “Can people successfully evacuate using crawling?” and “How fast should people be able to crawl during evacuation?” under current evacuation standards.

Knowing the performance capabilities and limitations of atypical locomotive behavior due to breathing zone restrictions may provide recommendations for evacuation route designs. Additionally, studying crawling activity in evacuation conditions may also be helpful to train emergency responders so that they can be more effective when performing rescue activities under the Immediately Dangerous to Life and Health (IDLH) conditions.

## 1.1 Research Objectives

Based on the lack of studies on adult crawling, research on the effect of posture on evacuation performance and physiological demands is warranted. Five different postures (Upright Walking (UW), Stoop-Walking (SW), Foot and Hand Crawling (FHC), Knee and Hand

Crawling (KHC), and Low Crawling (LC)) corresponding to five different breathing zone heights were examined to determine whether locomotive posture affected travel speed, travel distance and physiological workload. Kinematic data of different locomotive postures were also studied, including stride duration, stride length, interlimb coordination patterns, and points of contact to the ground. Therefore, the purpose of this research includes: 1) to evaluate the effect of different postures on crawling evacuation performance; 2) to quantify the physiological demands associated with different postures; and 3) to perform a kinematic analysis of atypical postural locomotion.

### 1.2 Research and Dissertation Organization

The chapters of this dissertation are organized according to the Auburn University dissertation guide. This dissertation is comprised of six chapters. Chapter One is a traditional introduction and Chapter Six is a traditional conclusion. Chapter Two is a comprehensive literature review of current standards and regulations related to evacuation exit routes, and the speed and physiological demands of human locomotion in different postures. Each of the remaining chapters is a stand-alone manuscript describing purpose, method, results, discussion, and conclusions of an experiment. Chapter Three reports velocities and maximum travel distances associated with different locomotive postures. Chapter Four examines the physiological demands of evacuation using atypical postures assumed by subjects under constrained conditions by measuring heart rate, respiratory response and perceived exertion. Chapter Five reports the kinematic analysis of different locomotive postures. The appendices contain details outlining the recruitment and participation of human subjects, Internal Review Board (IRB) consent forms, experimental data, and other information to support the results presented in the chapter manuscripts.

# Chapter 2

# Review of the Literature

The following review of the literature includes five parts: First, different types of evacuation were reviewed. Second, a specific investigation was performed to understand current standards for the design of emergency evacuation exits and routes. Third, a literature review was conducted to determine human movement speed in different postures. Fourth, a review of the literature was performed to ascertain the extent to which previous research has focused on the measurement and estimation of physiological demands for human locomotive activities. Last, a review of previous studies focusing on kinematic analysis of human locomotion was conducted. It is expected that a solid understanding of the studies and methods that have been used in the past will result in opportunities to identify gaps in the literature to further the findings and knowledge known about the area of study.

## 2.1 Definition of Evacuation

According to the definition from the Merriam-Webster dictionary, "evacuation is the immediate and urgent movement of people away from the threat or actual occurrence of a hazard" [Merriam-Webster, 2014]. Evacuations are more common than most people realize. Examples of evacuations range from small-scale evacuation of a building due to bomb threats, active shooter(s), or fire, to large-scale evacuation of geographical districts because of bad weather (flood, hurricane, etc.), military attack, or hazmat release. Evacuating a large population is an extremely complicated and time-consuming task, which primarily relies on the efficiency of evacuation plans and transportation systems and only marginally depends on individual performances. Large-scale evacuations are beyond the scope of the present study. The efficiency of a small-scale evacuation typically depends on the configuration of the structure and the movement ability of individuals [Franzese and Han, 2001]. Therefore, previous human evacuation performance studies have mainly focused on small-scale evacuations (e.g., building evacuation) [Kady and Davis, 2009a; Kady and Davis, 2009b; Davis, 2011; Nagai, Fukamachi, and Nagatani, 2006].

## 2.2 Standards for Emergency Evacuation Exit and Route Design

A specific investigation was performed to understand the current standards for small-scale emergency evacuation. Standards include the design of emergency evacuation exits and routes, maximum occupant load for certain structures, requirements for evacuation drills, and targeted evacuation times.

### 2.2.1 The Occupational Safety and Health Administration (OSHA) Standards

When an emergency occurs in a building, occupants are frequently advised to evacuate. Two frequently asked questions related to emergency evacuation are: “Can people successfully evacuate?” and “How fast can people evacuate?” The Occupational Safety and Health Administration (OSHA) highlights the importance of these questions by establishing standards for workplace emergencies and evacuations. These standards include the number of exit routes, width of exit routes, the safe use of exit routes, alarm systems, respiratory protection, fire detection systems, etc. [OSHA, 2015c].

OSHA (2015c) requires that “at least two (2) exit routes must be available in a workplace to permit prompt evacuation of employees and other building occupants during an emergency. More than two (2) exit routes must be available in a workplace if the number of employees, the size of the workplace, its occupancy, or the arrangement of the workplace is such that all employees might not be able to evacuate safely during an emergency” [OSHA, 2015c]. However, OSHA does not specify the number of occupants, the size of the workplace, or the arrangement of the building when two (2) exit routes are not enough for successful evacuation and when more than two (2) exit routes are needed.

According to the OSHA [2017], an adequate number of the exit routes to ensure successful evacuation from a building is typically verified by performing an emergency evacuation drill and/or preparing an Emergency Action Plan (EAP). OSHA [2017] states that “the purpose of an EAP is to facilitate and organize employers and employees’ actions during workplace emergencies.” However, an EAP is not a requirement for all businesses. Only businesses that involve the use of hazardous substances, or are subject to the provisions of the process safety management of highly hazardous chemicals standard, and hazardous waste operations are required to develop an EAP in compliance with 29 CFR 1910.38 [OSHA, 2015b].

In addition, OSHA does not require an evacuation demonstration before buildings or workplaces are placed in use. OSHA only recommends, but does not require, an emergency evacuation drill be conducted once each year. Lack of mandatory standards for EAP and evacuation drills may lead employers or building designers to specify and implement inadequate exit routes or to create an improper arrangement of exits based solely on guidance from OSHA.

### 2.2.2 National Fire Protection Association (NFPA) Standards

In general, NFPA has more comprehensive standards for exit route design than OSHA. Unlike the general requirement of at least two (2) exits for the workplace from OSHA [2015c], NFPA [2015] establishes more specific standards based on maximum occupant load. Maximum occupant load is the maximum number of people permitted in a certain area. According to the NFPA [2015], more exits are needed if the building permits a higher maximum occupant load. For example, four (4) exits are needed if maximum occupant load of a building is more than one thousand (1,000). Table 2.1 shows the minimum number of exits required for different maximum occupant loads by NFPA [2015].

Table 2.1. Number of Exits Required for Different Occupant Loads.

| Maximum Occupant Load | Minimum Number of Exits |
|---|---|
| 1-50 | 1 |
| 51-500 | 2 |
| 501-1,000 | 3 |
| More than 1,000 | 4 |

Apart from the standard for number of exits, NFPA also publishes a standard to require periodic fire drills for certain establishments [NFPA, 2015]. However, NFPA [2015] does not establish any targeted evacuation time for buildings or workplaces. NFPA only requires establishments to record their total time for evacuation drills.

NFPA [2015] suggests that an evacuation should be performed “as quickly as possible” and the evacuation time mainly depends upon the size and the type of building. NFPA [2015] states that “the intention for the evacuation drill is not to establish guidance for total evacuation time or set up standards for evacuation route or exit design, but for establishments to take evacuation safety into consideration and to inform occupants in the building of how to get out of the building in the quickest and safest way if an emergency were to occur.” In real emergencies, the total time required for fully evacuating a building or workplace is very important.

### 2.2.3 The International Building Code (IBC) Standards

The International Building Code (IBC) which is developed by the International Code Council (ICC) also establishes standards for building evacuation route and exit design. The code addresses the number of exits required for a structure based on its intended occupancy, which is very similar to NFPA [2015] standards [International Code Council, 2015].

Besides the number of exits, IBC [2015] also specifies a standard for the exit layout by defining and limiting the maximum distance to an exit. IBC enforces that the distance to an exit shall not exceed 250 feet (76.2 m) for a building with a sprinkler system, and shall not exceed 200 feet (60.9 m) for a building without a sprinkler system.

Although IBC [2015] standards are more comprehensive regarding evacuation route and exit design than OSHA [2015c] and NFPA [2015], those standards (number of exits, the maximum travel distance to an exit) are established and verified by opinions from a group of experts, and data from controlled experiments and/or evacuation drills. Controlled experiments and evacuation drills are typically performed in optimum environmental conditions, which may not properly represent real-world evacuation environments or actual individual evacuation performance.

### 2.2.4 Summary of Current Standards

There are relatively few organizations that establish standards for emergency evacuation route and exit design in the United States. Such standards provide guidance and mandatory rules for the design of evacuation routes and exits. A summary of existing standards and their contents are shown in Table 2.2. Summarizing the current standards for evacuation route and exit design from various standards making bodies is an essential first step to determine the adequate application of current safety standards to evacuation.

Table 2.2. Existing Standards for Evacuation Route and Exit Design.

| Organization | Document | Number of Exits | Maximum Distance to an Exit | Time Limit |
|---|---|---|---|---|
| OSHA | 29 CFR 1910 | At least two (2) | N/A | N/A |
| NFPA | Life Safety Code | Based on Maximum Occupant Load | N/A | N/A |
| ICC | IBC | Based on Maximum Occupant Load | 200 ft. (60 m) without sprinkler<br>250 ft. (76 m) with sprinkler | N/A |

A common deficiency among existing standards is that they are established based on optimum environmental conditions. In a real emergency, evacuation performance (basically evacuation movement speed) could be significantly affected by a deteriorating environment (e.g., severe fire conditions), and the performance of evacuees may differ from person to person (e.g., gender, overweight, aging, injured, etc.). Therefore, based on the current standards, it is relatively difficult to answer the questions: “Can people successfully evacuate?” and “How fast can people evacuate?” It is reasonable to look into the research of human movement in different environmental conditions to ascertain how much deteriorating environmental conditions impede human movement.

## 2.3 Human Movement Speed

### 2.3.1 Human Movement during Emergency Evacuation

According to the Emergency Action Plan (EAP) standards, OSHA [2017], evacuation should be executed as quickly and safely as possible. However, in real emergency evacuations, the deterioration of environmental conditions, in terms of heat, smoke, combustion gases, etc., could become obstacles that prevent, or at least slow, evacuation. Sometimes, environmental conditions may force people to adopt atypical locomotive behaviors or physical responses to evacuate.

Several previous studies have demonstrated that environmental factors such as heat and smoke had significant effects on human movement speed. One study by Sander et al. [2011] measured human walking speed in different levels of visual field limitations. The results of the study indicated that a decrease in visual field size led to a significant decrease in walking speed. Similar results were also found in two other research studies. Akizuki et al. [2007] considered the effect of smoke density on walking speed, and Jin and Yamada [1989] conducted an experimental study of human behavior in smoke filled corridors.

In real fire emergencies, hot air and smoke rise. Therefore, to get access to a better visual field and a cooler and cleaner atmosphere, people may stay low and close to the ground. According to the OSHA [2017], a majority of deaths in severe fire conditions are not caused by direct burns, but smoke inhalation. Statistics from NFPA [2015] show that about 80% of fire deaths are caused by smoke inhalation. In fire conditions, smoke generated by incomplete burning contains hot and toxic chemicals, such as carbon monoxide, sulfur dioxide, nitrogen oxide, etc., which cause the lungs and the airway to become irritated, swollen, and blocked. The damaged airway and lungs then prevent oxygen from getting into the blood, which leads to respiratory failure. OSHA [2015d] has defined breathing zone as "… within a ten-inch radius of the worker's nose and mouth." To avoid smoke inhalation in fire evacuation, people are forced to change the height of their breathing zones and move their noses and mouths as close as possible to the ground to access breathable air. Altering the height of the breathing zone leads to the adoption of atypical locomotive behaviors. According to the fire evacuation tips from both OSHA [2017] and NFPA [2015], it is recommended that evacuees crawl low, under the smoke to breathe cleaner air, and avoid exposure to the smoke during evacuation.

Interestingly, different types of crawling were used by humans during locomotion according to previous studies. Cott and Kinkade [1972] considered a normal crawling position to be when a subject rested on knees and flattened palms with arms and thighs perpendicular to the floor and feet comfortably extended and spaced. The same definition was also reported in a study by MacLellan et al. [2012]. A study by Moss [1934] considered crawling to include another "all-fours" technique where feet (not knees) and hands were used for locomotion. Moreover, a study by Gallagher et al. [2011] mentioned a "two-point" crawling technique in which the hands were not used to support the body, and crawling was performed by walking on the knees alone. This technique is most commonly utilized in underground mining, especially when an item needs to be held in the hands while moving a short distance.

Previous studies indicated that people adopt different types of crawling depending on the environment they are in and the task they are performing [Gallagher et al., 2011; Patrick, Noah, and Yang, 2009]. Therefore, during a fire evacuation, people may adopt different crawling postures based on the breathing zone they seek and the tasks they need to perform, such as opening/closing a door, holding items in hands, crawling over obstacles, etc.

### 2.3.2 Movement Speeds for Walking and Atypical Postures

In emergency evacuations, people may seek to use atypical locomotive behaviors other than upright walking. Several previous studies have investigated and measured human movement speed in different postures. Walking, the most common posture used by human beings during locomotion, is defined as "a posture that advances or travels on foot at a moderate speed or pace" by the Merriam-Webster Dictionary [Merriam-Webster, 2014]. Most previous studies measured normal and maximum walking speeds and examined personal characteristics such as age, gender, and Body Mass Index (BMI) on walking speed [Bohannon, 1997; Knoblauch, Pietrucha, and Nitzburg, 1996; Browning, Baker, Herron, and Kram, 2006; Bendall, Bassey, and Pearson, 1989; Dal, Erdogan, Resitoglu, and Beydagi, 2010; Bohannon, Andrews, and Thomas, 1996; Murry, Kory, Clarkson, and Speic 1966]. Interestingly, for the convenience of measuring walking speed, most of those studies were conducted on treadmills.

Bohannon [1997] performed a study to measure comfortable and maximum walking speeds and found that walking speed varied among people. Bohannon [1997] recruited two hundred and thirty (230) healthy volunteers aged twenty (20) to seventy-nine (79) years old. He reported the mean comfortable walking speed ranged from 4.17 ft/s (1.27 m/s) for women in their seventies to 4.79 ft/s (1.46 m/s) for men in their forties. Mean maximum gait speed ranged from 5.74 ft/s (1.75 m/s) for women in their seventies to 8.30 ft/s (2.53 m/s) for men in their twenties [Bohannon, 1997]. Knoblauch et al. [1996] measured the mean normal walking speed at 4.10 ft/s (1.25 m/s) for subjects aged from fourteen (14) to sixty-four (64). Both studies concluded that age had a significant effect on walking speed. In addition, a more recent study by

Browning et al. [2006] measured the average preferred speed of walking at 4.66 ft/s (1.42 m/s). In their study, both obese and non-obese subjects were recruited to walk at various speeds on a treadmill. Results indicated that obesity significantly affected one's preferred walking speed. Interestingly, previous studies reached a consensus for normal walking speed at around 4.27 ft/s (1.3 m/s), but reported maximum walking speeds ranged from 5.74 ft/s (1.75 m/s) to 9.61 ft/s (2.93 m/s) [Bohannon, 1997; Knoblauch et al., 1996; Browning et al., 2006; Bendall et al., 1989; Dal et al., 2010; Bohannon et al., 1996; Murry et al., 1966]. Abundant support exists for a 'normal' walking speed of 3.0 MPH (4.40 ft/s (1.34 m/s)). 'Normal' in this aspect refers to the 100% pace ('normal' pace) that industrial engineers use when conducting time studies [Freivalds and Niebel, 2012].

Apart from general walking speed, there are also some studies considering walking speed in an evacuation context. Normal walking speeds reported in evacuation studies were found to be very similar to speeds reported in general walking studies. Kady and Davis [2009a] performed one of those evacuation studies and measured the normal walking speed at 4.86 ft/s (1.48 m/s). A similar study conducted for improving evacuation modeling by Muhdi et al. [2006] measured normal and maximum walking speeds at 4.33 ft/s (1.32 m/s) and 7.05 ft/s (2.15 m/s) respectively. In addition to measuring walking speed, a study entitled, "Evacuation of Crawlers and Walkers from Corridor through an Exit" conducted by Nagai et al. [2006] recorded the walking escape time through different width exits: 0.4 m, 0.8 m, 1.2 m and 1.6 m. Average walking speed was reported at 3.94 ft/s (1.2 m/s) in their study. Nagai et al. [2006] indicated that exit width and evacuee density had significant effects on evacuation time.

In the case of atypical locomotive behaviors other than upright walking, some previous studies measured the walking speed and also examined atypical movement speeds (e.g., crawling)

[Muhdi et al., 2006; Kady and Davis, 2009a; Kady and Davis, 2009b]. However, compared to the walking speed studies, there are relatively few studies considering atypical postural movements and even fewer studies reporting atypical postural movement speeds in an evacuation context. Muhdi et al. [2006] conducted one of the few studies that measured normal and maximum crawling speeds. It should be noted that Muhdi et al. [2006] used four-point crawling technique (crawling with both hands and knees) in their study. The average normal crawling speed was measured at 2.33 ft/s (0.71 m/s), and average maximum crawling speed was measured at 4.82 ft/s (1.47 m/s). In addition, a study by Kady and Davis [2009a] was conducted to investigate occupants' crawling speed compared to walking speed in an evacuation context. The effect of occupants' characteristics, gender and Body Mass Index (BMI), on crawling was also considered in their study. Eighteen (18) subjects participated in this study to crawl 100 feet (30.5m). The results of this study showed that the four-point crawling speed ranged from 1.77 ft/s (0.54 m/s) (obese female) to 3.05 ft/s (0.93 m/s) (non-obese male). Another research study also by Kady and Davis [2009b] examined the evacuation time for crawling a distance of 100 feet (30.5m) in both straight and indirect (with turns) routes. The indirect route consisted of five (5) 90-degree turns (changes of direction), and was marked every twenty (20) feet (6.1 m). Significant differences in evacuation times between crawling a straight route and an indirect route were detected. Average crawling speed for the straight route measured in this study was very close to average crawling speed measured in their previous study [Kady and Davis, 2009a]. In addition, this study also reported that there are significant effects of gender and Body Mass Index (BMI) on crawling evacuation time.

In general, non-evacuation studies reported slower normal and maximum crawling (with both hands and knees) speeds. For example, Bajd, Zefran, and Kralji [1995] reported a maximum four-point crawling speed of 2.10 ft/s (0.64 m/s). In another study by Babic, Karcnik, and Bajd [2001], subjects averaged 1.25 ft/s (0.38 m/s), 1.94 ft/s (0.59 m/s) and 2.69 ft/s (0.82 m/s) for slow, medium and fast four-point (with both hands and knees) crawling. A study by Patrick et al. [2009] examined a wide range of crawling velocities from 0.72 ft/s (0.22 m/s) (infant crawling) to 4.40 ft/s (1.34 m/s) (maximum adult crawling). Crawling posture used in their study was also four-point crawling (with both hands and knees), and their study was performed on a treadmill [Patrick et al., 2009].

The previous literature on human crawling performance indicates that four-point crawling posture (with both hands and knees) was the most frequently studied [Cott and Kinkade, 1972, MacLellan et al., 2012]. Relatively few studies have investigated other crawling postures. One of those few studies, by Gallagher et al. [2011], examined two types of crawling: four-point crawling (with both hands and knees) and two-point crawling (with just knees). Average four-point crawling speed observed in their study was 1.64 ft/s (0.5 m/s), which was slower than those observed in previous evacuation studies [Kady and Davis, 2009a; Kady and Davis, 2009b], but was close to velocities observed in non-evacuation crawling studies [Patrick et al., 2009; Bajd et al., 1995; Babic et al., 2001]. Gallagher et al. [2011] also measured two-point crawling (with just knees) speed, at a much slower velocity: 1.05 ft/s (0.32m/s). Another four-point crawling technique (crawling with hands and feet) was mentioned by MacLellan et al. [2012]. MacLellan et al. [2012] measured the speed of four-point crawling (with hands and feet) at 2.79 ft/s (0.85 m/s), which was much faster than the regular four-point crawling (with hands and knees). Except for the studies by Gallagher et al. [2011] and MacLellan et al. [2012], no other study measuring crawling speed other than four-point crawling (with both hands and knees) was found.

### 2.3.3 Summary of Human Movement Literature

Literature search results for human locomotion speed is shown in Table 2.3, Table 2.4, Figure 2.1 and Figure 2.2. Searching and summarizing previous studies for human locomotion speed provides references to compare the human locomotion speed in different postures and evidence to evaluate human evacuation performance in emergency scenarios.

Table 2.3 shows that most human locomotive activity studies have focused on the effects of the occupant's demographic characteristics and environmental factors on human locomotion. Table 2.4, Figure 2.1 and Figure 2.2 summarize normal walking and crawling speeds reported by previous literature. From Figure 2.1 and Figure 2.2, it can be seen that relatively few previous crawling studies were conducted in an evacuation context. Normal walking speeds are very close between non-evacuation and evacuation based studies, while normal four-point crawling (with both hands and knees) speeds in evacuation studies (average at 2.82 ft/s (0.86 m/s)) are much higher than speeds in non-evacuation studies (average at 1.80 ft/s (0.55 m/s)). In addition, most previous crawling studies only investigated the posture of four-point crawling (with both hands and knees). No other crawling postures have been fully studied.

Table 2.3. Literature Search Results for Human Locomotion Speed.

| Author(s) (Year) | Walking Speed | Crawling Speed | Evacuation-based Study | Occupants' Characteristics | Environmental Factors |
|---|---|---|---|---|---|
| MacLellan et al., 2012 | | Yes | | | |
| Gallagher et al., 2011 | | Yes | | | Yes |
| Sander et al., 2011 | Yes | | | | Yes |
| Dal et al., 2010 | Yes | | | Yes | Yes |
| Kady and Davis, 2009a | Yes | Yes | Yes | Yes | |
| Kady and Davis, 2009b | | Yes | Yes | Yes | Yes |
| Patrick et al., 2009 | | Yes | | Yes | |
| Akizuki et al., 2007 | Yes | | | Yes | Yes |
| Browning et al., 2006 | Yes | | | Yes | |

Table 2.3. (Cont'd) Literature Search Results for Human Locomotion Speed.

| Author(s) (Year) | Walking Speed | Crawling Speed | Evacuation-based Study | Occupants' Characteristics | Environmental Factors |
|---|---|---|---|---|---|
| Muhdi et al., 2006 | Yes | Yes | Yes | Yes | |
| Nagai et al., 2006 | Yes | Yes | Yes | | Yes |
| Babic et al., 2001 | | Yes | | Yes | |
| Bohannon, 1997 | Yes | | | Yes | |
| Bohannon et al., 1996 | Yes | | | Yes | |
| Knoblauch et al., 1996 | Yes | | | Yes | |
| Bajd et al., 1995 | | Yes | | Yes | |
| Jin and Yamada, 1989 | Yes | | | Yes | Yes |
| Bendall et al., 1989 | Yes | | | Yes | Yes |

Table 2.3. (Cont'd) Literature Search Results for Human Locomotion Speed.

| Author(s) (Year) | Walking Speed | Crawling Speed | Evacuation-based Study | Occupants' Characteristics | Environmental Factors |
|---|---|---|---|---|---|
| Murray et al., 1966 | Yes | | | | Yes |
| Moss, 1934 | | Yes | | | Yes |

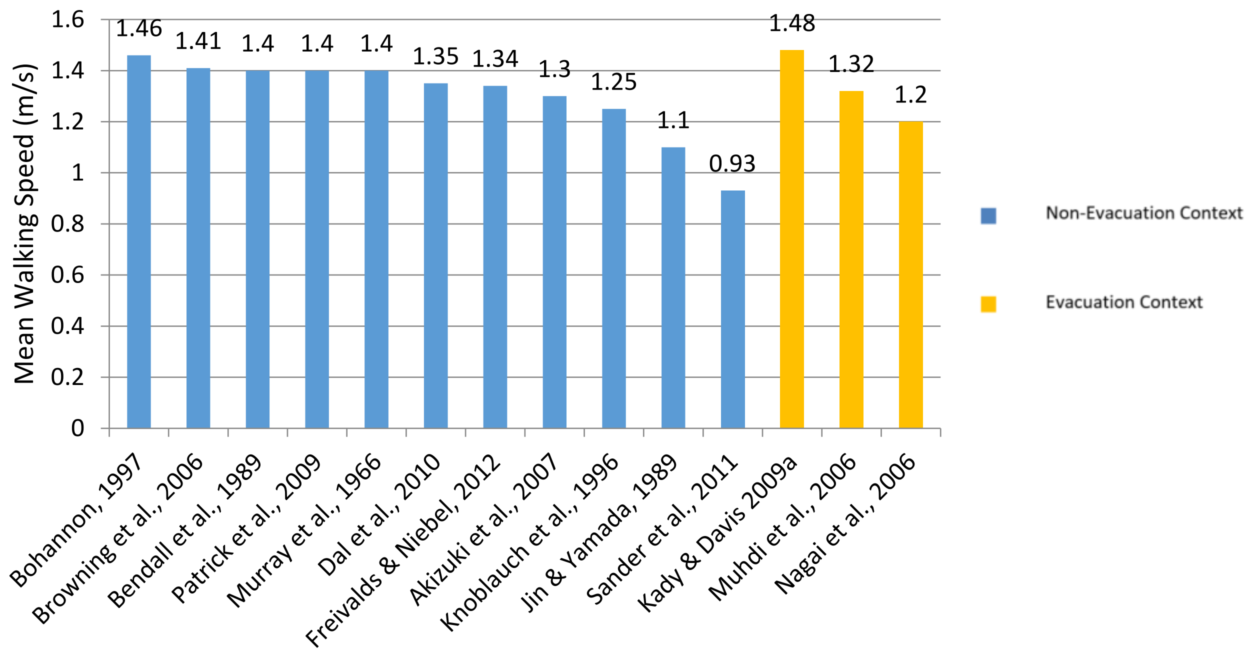


Figure 2.1. Literature Search Results for Normal Walking Speed.

Table 2.4. Literature Search Results for Normal Crawling Speed.

| Author(s) (Year) | Crawling Types | Normal Crawling Speed (m/s) |
|---|---|---|
| MacLellan et al., 2012 | Four-point (hands and feet) | 0.85 |
| Gallagher et al., 2011 | Stoop-Walking<br>Two-point (knee)<br>Four-point (hands and knees) | 1.01<br>0.32<br>0.5 |
| Kady and Davis, 2009a | Four-point (hands and knees) | 0.93 |
| Kady and Davis, 2009b | Four-point (hands and knees) | 0.87 |
| Patrick et al., 2009 | Four-point (hands and knees) | 0.45 |
| Muhdi et al., 2006 | Four-point (hands and knees) | 0.71 |
| Nagai et al., 2006 | Four-point (hands and knees) | 0.73 |
| Babic et al., 2001 | Four-point (hands and knees) | 0.59 |
| Bajd et al., 1995 | Four-point (hands and knees) | 0.62 |
| Moss, 1934 | Stoop-Walking<br>Four-point (hands and knees) | 0.9<br>0.5 |

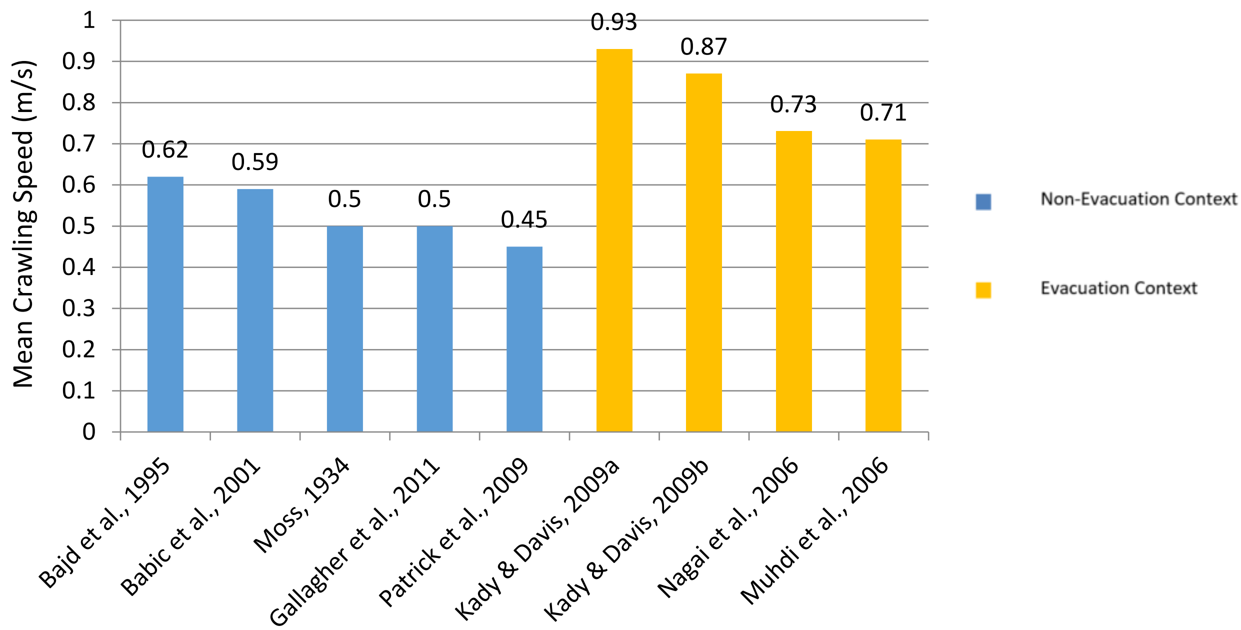


Figure 2.2. Literature Search Results for Normal Four-point Crawling Speed.

### 2.4 Physiological Demands during Human Movement

As mentioned before, it is reasonable to expect that humans seek to evacuate a threatening environment in an expeditious manner. Being bipedal, the fastest locomotive means of movement for humans is walking, if running is not considered in egress situations. However, in severe fire evacuation, occupants may be forced to crawl low under the smoke to avoid hazardous effects and to achieve successful evacuation. Previous studies indicated that crawling is a relatively higher physiologically demanding activity compared to bipedal movement [Moss, 1934; Morrissey et al., 1985; Davis, 2011]. Knowing the physiological demands of human movement can be critical in determining whether people can successfully evacuate.

### 2.4.1 Measurement of Physiological Demands

Physiological demands, or the quantification of energy expenditure and exertion, can be measured by a variety of methods, but is best explained by several parameters including Volume of Oxygen Consumption ($VO_2$), Volume of Carbon Dioxide Production ($VCO_2$), Ventilation Rate ($V_E$), Respiratory Exchange Ratio (RER), and Heart Rate (HR) [Armstrong, Brubaker, Whaley and Otto, 2006; Bhattacharya and McGlothlin, 2012].

"Occupational Ergonomics: Theory and Applications" suggests that the measurement of physiological demands in the workplace is one of the best ways to analyze and predict worker performance [Bhattacharya and McGlothlin, 2012]. According to Bhattacharya and McGlothlin [2012], in order to quantify the physiological demands of a task, parameters such as HR, $VO_2$, and $V_E$ were studied. Bhattacharya and McGlothlin [2012] suggested that direct measures of oxygen consumption provide the best estimation of physiological demands, and indicated that Heart Rate (HR) is useful in predicting physiological demands but it is less reliable than direct oxygen consumption measures due to individual differences in the relationship between heart rate and energy expenditure. In fact, many previous studies in the workplace did use HR and $VO_2$ to quantify physiological demands [Malchaire, Wallemacq, Rogowsky, and Vanderputten, 1984; Amelsvoort, Schouten, Maan, Swenne, and Kok, 2000; Bouchard and Trudeau, 2008]. Therefore, a review of the measurement of $VO_2$ and HR was performed as follows:

Volume of Oxygen Consumption ($VO_2$)

$VO_2$ is a measure of the volume of oxygen used by a human body [Plowman and Smith, 2010]. $VO_2$ is expressed either as an absolute rate (for example, liters of oxygen per minute (L/min)) or as a relative rate (for example, milliliters of oxygen per kilogram of body mass per minute (mL/(kg·min)). According to Plowman and Smith [2010], the latter expression is often used to compare the performance of endurance. Plowman and Smith [2010] also mentioned that normal resting $VO_2$ is 0.25 - 0.5 L/min.

Devices to Measure Oxygen Consumption

The most classical method to measure oxygen consumption was to collect expired air in a Douglas bag (DB). While this technique has been widely used, it is cumbersome, limited to fairly short collection periods, and requires timed collections of expired gas and subsequent analysis of expired oxygen and carbon dioxide concentrations [Patton, 1997]. According to Patton [1997], one method to overcome those limitations is to use portable respiratory measurement systems.

There are several advantages to use a portable respiratory measurement system. Patton [1997] claimed that a portable system not only is capable of measuring the volume of the expired or inspired air for a longer collection period, but also is capable of measuring gas concentrations so that oxygen uptake can be calculated by the instrument immediately. In addition, such systems can be light enough to be easily transported and are typically battery operated, with the analysis of both gas volume and concentration performed rapidly using integrated a high-speed microprocessor. According to Patton [1997], there are three portable systems widely used to provide a continuous measurement of oxygen consumption and ventilation for a long period of testing: (1) the Oxylog, (2) the Total Energy Expenditure Measurement system (TEEM), and (3) the COSMED K4b2 [Patton, 1997].

Average Heart Rate (HRavg), Resting Heart Rate (HRrest), and Maximum Heart Rate (HRmax)

The Average Heart Rate (HRavg) is the number of heartbeats per unit of time. The Resting Heart Rate (HRrest) is defined as the heart rate when subjects are in a normal temperature environment and a rested condition without any exertion. The typical HRrest for an adult is 60 - 100 beats per minute (bpm), depending on subject's physical condition and age. The maximum heart rate (HRmax) on the other hand is the highest heart rate an individual can achieve without severe problems through exercise stress [Guyton and Hall, 2005].

Several previous studies examined subject’s HRmax and provided equations to estimate the individual’s HRmax. The most widely cited equation for estimating HRmax is: HRmax = 220 – age (bpm), from the American College of Sports Medicine (ACSM) [2007]. Other equations for HRmax include: 1) HRmax = 208 − (0.7 × age) (bpm) from Tanaka, Monahan, and Seals [2001]. 2) HRmax = 205.8 − (0.685 × age) (bpm) from Robergs and Landwehr [2002], and 3) HRmax = 206 − (0.88 × age) (bpm) from Gulati et al. [2010]. These equations were usually regression equations derived from research experiments with more than 500 data points.

Devices to Measure Heart Rate

There are two types of methods for heart rate measurement: manual method and monitor method. Manual method includes radial pulse (wrist) measurement and carotid pulse (neck) measurement, while monitor methods include electrocardiogram (ECG) and heart rate monitors.

Several previous studies validated the reliability of a heart rate monitor compared to electrocardiogram (ECG) [Weippert et al., 2010; Laukkanen and Virtanen, 1998; Gamelin, Berthoin, and Bosquet, 2006]. The results of those studies confirmed that heart rate data obtained from the heart rate monitors appeared to be as reliable as those obtained from ECG. Therefore, both heart rate monitors and ECG were widely used in previous physiological demands measurement studies [Weippert et al., 2010; Laukkanen and Virtanen, 1998; Gamelin et al., 2006].

### 2.4.2 Physiological Demands for Human Movement

Walking, the most common locomotive method people adopt, has been reported in previous studies to be much less physiologically demanding than other bipedal locomotive techniques (e.g., jogging or running) [Walt and Wyndham, 1973; Dill, 1965; Flynn, Connery, Smutok, Zeballos, and Weisman, 1994; Francis and Hoobler, 1986; Jones, Toner, Daniels, and Knapik, 1984; Fudge et al., 2007].

A study by Flynn et al. [1994] measured the physiological demands of backward/forward walking (at a constant speed of 107.2 m/min) and backward/forward running (at a constant speed of 160.8 m/min). Flynn et al. [1994] controlled the walking and running speed by conducting the study on a treadmill. This study quantified physiological demands by measuring several parameters including $V_E$, $VO_2$, RER, HR, and both pre and post study lactate levels. Results indicated that backward movement tended to cost more energy than forward movement. Flynn et al. [1994] also concluded that running activities ($VO_2$=27.8 mL/(kg·min), HRavg=139 bpm) were more physiologically demanding than walking activities ($VO_2$=18.7 mL/(kg·min), HRavg=106 bpm). Jones et al. [1984] examined the energy costs of walking and running. Fourteen (14) male subjects were recruited and performed walking and running activities on a treadmill. Three levels of walking speed (66 m/min, 93.3 m/min and 121.7 m/min) and three levels of running speed (148.3 m/min, 175 m/min and 201.7 m/min) were used in their study. Subjects' mean $VO_2$ for walking in their study was measured at 24.1 mL/(kg·min). A study by Davis [2011] reported average $VO_2$ at 13 mL/(kg·min), and $V_E$ at 25 L/min for normal speed (4.40 ft/s (1.34 m/s)) walking.

As expected, physiological demands for walking activities reported in other previous studies are very similar to the forward walking physiological demands reported by Flynn et al. [1994]. Most previous studies measured $VO_2$ for normal speed walking at around 20 mL/(kg·min) [Walt and Wyndham, 1973, Dill, 1965, Jones et al., 1984; Mattsson, Larsson, and Rössner, 1997; Martin, Rothstein, and Larish, 1992; Pollock et al., 1971].

Previous studies also detected the effects of subjects' characteristics (age, gender, Body Mass Index (BMI)) on the metabolic costs of walking. One of those studies by Mattsson et al. [1997] indicated that obese women walked more slowly, and had a higher $VO_2$. Average $VO_2$ for obese women during walking was around 1.2 ± 0.2 L/min higher than non-obese women. Age effects on physiological demands were found by Martin et al. [1992]. A statistically significant age effect on walking aerobic demand was observed in their study, with older subjects (66-86 years old) showing an 8% higher mean aerobic demand than younger (18-28 years old) subjects. [Martin et al., 1992].

Table 2.5 shows the literature search results for physiological demands ($V_E$, $VO_2$, HRavg, and HRmax) of normal-speed walking.

Table 2.5. Literature Search Results for Physiological Demands of Walking.

| Author(s) (Year) | $V_E$ (L/min) | $VO_2$ (mL/(kg·min)) | HRavg (bpm) | HRmax (bpm) |
|---|---|---|---|---|
| Davis, 2011 | 25 | 13 | 100 | 110 |
| Mattsson et al., 1997 | | 21.0 | | |
| Flynn et al., 1994 | 36.9 | 18.7 | 106 | 134 |
| Martin et al., 1992 | | 12.96 | | |
| Jones et al., 1984 | | 24.1 | 109 | |
| Walt and Wyndham, 1973 | 40.1 | 20.3 | | |
| Pollock et al., 1971 | | 29.1 | 95 | |
| Dill, 1965 | | 15.0 | 76 | |

In addition, The American College of Sports Medicine (ACSM) offers equations to estimate oxygen consumption for walking and running activities [ACSM, 2007]. According to the ACSM, oxygen consumption for walking is: $VO_2$ = 0.1 mL/(kg·min) x $V_1$ (km/h) + 1.8 mL/(kg·min) x $V_2$ (km/h) + 3.5 mL/(kg·min), while oxygen consumption for running is: $VO_2$ = 0.2 mL/(kg·min) x $V_1$ (km/h) + 0.9 mL/(kg·min) x $V_2$ (km/h) + 3.5 mL/(kg·min), where $V_1$

(km/h) is horizontal movement speed, $V_2$ (km/h) is vertical ascent speed and 3.5 is estimated resting oxygen consumption. ACSM [2007] also provides regression equations to predict the expected oxygen consumption of an individual based upon activity level, age and gender. The oxygen consumption equation for active men is: $VO_2 = 69.7$ mL/(kg·min) - (0.612 mL/(kg·min) x age) and the equation for active women is: $VO_2 = 42.9$ mL/(kg·min) - (0.312 mL/(kg·min) x age). The equation for sedentary men is: $VO_2 = 57.8$ mL/(kg·min) - (0.445 mL/(kg·min) x age) and the equation for sedentary women is: $VO_2 = 42.3$ mL/(kg·min) - (0.356 mL/(kg·min) x age).

By using these ACSM equations, $VO_2$ for running, walking and sedentary activities can be estimated. However, ACSM does not provide any oxygen consumption estimation equations for atypical postural locomotion, such as crawling.

Compared to the studies focused on the metabolic cost of walking activities, few studies considered the physiological demands of crawling. The available literature suggests that crawling results in significant physiological demands as well as physical discomfort [Moss, 1934; Davis 2011]. Crawling emerged as a very inefficient means of locomotion for humans with significant limitations in speed and high metabolic demands [Morrissey et al., 1985].

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 hand and knee crawling activities. Davis [2011] conducted this study on a treadmill and evaluated the Heart Rates (HR), Volumes of Oxygen Consumption ($VO_2$), Ventilation Rates ($V_E$) and Ratings of Perceived Exertion (RPE) for crawling and walking. Results indicated that HRavg in the crawling trial was significantly higher (63.8 bpm higher) than in the walking trial, average $VO_2$ in the crawling trial was significantly higher (10.8 mL/(kg·min) higher) than in the walking trial and average $V_E$ in the crawling trial was significantly higher (33.47 L/min higher) than in the walking trial.

Another study by Moss [1934] examined the physiological costs associated with normal walking, a “half-stoop” (80% full stature), a “full-stoop” (60% full stature), and crawling with hands and feet (50% full stature). The results of that study suggested that the half-stoop, full-stoop and hands and feet crawling conditions increased the metabolic demands of locomotion by 20%, 66% and 73%, respectively. Morrissey et al. [1985] performed another study on the metabolic costs of crawling and stoop-walking by using more posture levels (100%, 90%, 80%, 70%, and 60% of full stature). The results of their study indicated that as the task posture became more stooped, there were marked increases in metabolic costs [Morrissey et al., 1985].

Instead of using stoop-walking posture, a study by Abitbol [1988] entitled, “Effect of Posture and Locomotion on Energy Expenditure” measured metabolic costs of human bipedal stance and locomotion, and quadrupedal stance and locomotion (hands and feet crawling). Thirty-one (31) healthy adults (age from seventeen (17) to twenty-five (25)) were recruited to travel with both bipedal and quadrupedal postures at 3.22 km/h on a treadmill. Results showed that during quadrupedal locomotion, subjects’ $VO_2$, RER and HR increased by 423%, 355% and 91% comparing to bipedal locomotion. Abitbol [1988] also mentioned that during quadrupedal locomotion tests, thirteen (13) out of thirty-one (31) subjects required short periods of rest and One (1) subject almost fainted towards the end of the task.

Previous literature indicates that stoop-walking and crawling result in significant physiological demands as well as physical discomfort. As mentioned before, atypical postures (e.g., stoop-walking and crawling) are sometimes adopted in emergency evacuation conditions.

However, there are no previous studies measuring the physiological demands of atypical postural locomotion in an evacuation context.

### 2.4.3 Summary of Literature

Physiological demands, or the quantification of energy expenditures and exertions, can be measured by a variety of methods, but is best explained by several parameters including $VO_2$, $VCO_2$, $V_E$, RER, and HR [Armstrong et al., 2006; Bhattacharya and McGlothlin, 2012]. Most previous studies used respiratory response and heart rate to quantify physiological demands of different activities. Available literature suggests that crawling results in significantly higher physiological demands than walking. However, very few previous studies were done to quantify physiological demands for crawling evacuation.

## 2.5 Kinematic Analysis of Human Crawling

As mentioned above, atypical locomotion, such as stoop-walking and crawling, are methods of locomotion that are typically used by humans in emergency evacuation. However, a limited number of previous studies were conducted on the kinematic analysis of locomotion with different postures. Previous studies analyzed the kinematic features of crawling on knees [Gallagher et al. 2011], hands and knees [Gallagher et al., 2011; Babic et al., 2001; Wannier, Bastiaanse, Colombo., and Dietz., 2001; Sparrow, 1989], and hands and feet [Patrick et al., 2009; MacLellan et al., 2012; Getchell, Forrester, and Whitall, 2001; Sparrow, 1989; Sparrow and Newell, 1994]. All previous kinematic analyses of crawling activity were conducted with a travel distance less than 50 feet (15.2 m). In addition, none of those studies were performed in an evacuation context.

Patrick et al. [2009] performed a study to examine the interlimb coordination patterns in four-point crawling (with both hands and feet) tasks. In their study, interlimb coordination patterns were assessed and quantified by the Ipsilateral Phase Lag (IPL). Patrick et al. [2009] defined the IPL as the delay between the stance phase of the left arm and the stance phase of the left leg. They pointed out that an IPL value of 50% indicated limbs entered stance alternately, which was defined as a "trot-like" gait, where the diagonal limbs entered stance around the same time. An IPL value of 0% or 100% indicated a "pace-like" gait, in which ipsilateral limbs contacted the ground around the same time, while an IPL value between a pace-like gait and a trot-like gait indicated "no pairing of limbs", with the four limbs entering stance equally spaced in time.

A study by MacLellan et al. [2012] also examined four-point crawling (with both hands and feet) behavior in human adults. Kinematics data from this study were recorded by a 9-camera Vicon system. Just as in the study by Patrick et al. [2009], Ipsilateral Phase Lag (IPL) between upper and lower limbs was also determined by the delay between the stance phase of the left arm and the stance phase of the left leg. The results of the study indicated that the number of limbs (four, three, or two) supporting the whole body weight depended on the speed and the instant of the gait cycle. IPL analysis also showed that upper and lower limbs did not differ significantly as a function of crawling speed or test track inclination. Overall, limb pairing (IPL ~25%) was rarely observed in their study. However, participants exhibited a "diagonal" pattern (IPL close to 50%) and a "lateral" pattern (IPL close to 0%) in hands and feet crawling, and these patterns did not change between crawling conditions.

In addition, a study by Wannier et al. [2001] examined arm and leg coordination in humans during walking, crawling and swimming activities. The results of this study indicated that arm to leg coordination observed in walking activity was also present during other locomotion activities (crawling and swimming).

Apart from hands and feet crawling, Gallagher et al. [2011] performed a study to analyze the kinematics of hands and knees crawling. Their results indicated that there was a significant variability in interlimb coordination in contact patterns. Interestingly, a study by Sparrow [1989] reported that infants had greater variability in their creeping gait patterns, while adult creeping gait patterns were less variable and more consistent. The results also indicated that hands and knees crawling had a gait pattern greatly different from hands and feet crawling.

Further, a study by Babic et al. [2001] assessed hands and knees crawling in three different speed levels. Babic et al. [2001] recorded the gait patterns of slow (1.25 ft/s (0.38 m/s)), normal (1.94 ft/s (0.59 m/s)), and fast (2.69 ft/s (0.82 m/s)) crawling for five male subjects. The study concluded that as speed increased, crawling tended to change from three or four-point stance phases to two-point stance phases (one hand and its contralateral knee were on the ground), which led to a dynamically unstable state.

No kinematic analysis of human crawling has been performed in an evacuation context. Studying crawling kinematics can provide guidance to evaluate evacuation performance and promote evacuation route design.

## 2.6 Research Gaps

1) In severe fire conditions, smoke, heat and combustion gases rise. Both OSHA [2017] and NFPA [2015] recommend evacuees crawl low under smoke during evacuation. However, most previous evacuation studies only focused on performance of walking or running. Crawling evacuation has not been well addressed.

2) OSHA [2015d] has defined breathing zone as "…within a ten-inch radius of the worker's nose and mouth." During an evacuation, evacuees may be forced to adopt different atypical locomotive techniques other than upright walking in order to access different breathing zone heights. Several previous studies investigated four-point crawling (with both hands and knees) performance during evacuation, while no other atypical locomotive postures (e.g., stoop-walking, hands and feet crawling, army crawling, etc.) have been studied in depth.

3) OSHA [2015c], NFPA [2015] and ICC [2015] standards (e.g., number of exits, maximum distance to an exit) for evacuation route design were established based on opinions from a group of experts, limited experimental data, and controlled evacuation drills. OSHA [2015c], NFPA [2015] and ICC [2015] did not clarify how those opinions and experimental data were attained. Questions like "how fast can people crawl in an emergency evacuation?" and "how far are people able to crawl to evacuate?" may not be taken into consideration when standards were established.

4) Previous evacuation studies focused on measuring metabolic costs of bipedal locomotion. Only a limited number of research studies were performed to examine physiological demands of crawling evacuation by measuring subjects' Heart Rate (HR) data. Very few previous studies investigated the respiratory response of crawling for evacuation purposes. The

American College of Sports and Medicine (ACSM) provides equations to estimate oxygen consumptions for running, walking and sedentary activities, but they do not provide equations for crawling.

5) Very few previous studies considered kinematics of atypical postural locomotion and no kinematic analysis of human crawling has been performed in an evacuation context.

A review of the literature suggests several promising research topics: 1) evaluation of evacuation performance (e.g., speed, distance, etc.) of different crawling postures; 2) evaluation of physiological demands of crawling; and 3) kinematic analysis of atypical postural locomotion.

Chapter 3

# The Effects of Breathing Zone Restrictions on Locomotion during Evacuation

## 3.1 Abstract

Humans may adopt atypical locomotive postures due to breathing zone restrictions during emergency evacuations. With the exception of walking upright, the effect of locomotion strategies on evacuation velocities is sparsely researched. This study evaluated human locomotion velocity and travel distance as a function of breathing zone height using different locomotive postures. Twenty-four (24) healthy college students (12 males and 12 females), aged from 19 to 30, participated in this study by traveling up to 300 feet (91.4 m) using five different postures: Upright Walking (UW), Stoop-Walking (SW), Foot and Hand Crawling (FHC), Knee and Hand Crawling (KHC), and Low Crawling (LC). Results of the study indicated that locomotive postures affect human velocity and travel distance. Crawling velocities were significantly slower than both bipedal velocities ($p<0.05$). Of the three crawling postures, FHC was faster ($p<0.05$) than the other two (KHC and LC). Average velocities for FHC, KHC and LC were measured at 3.94 ft/s (1.20 m/s), 2.77 ft/s (0.84 m/s) and 2.53 ft/s (0.77 m/s), respectively. Additionally, velocities in all crawling postures decreased significantly after the first thirty (30) feet (9.14 m) of travel. The average maximum crawling distance measured in this study was less than 250 feet (76.2 m). Results of the study provide additional guidance about the effects of different postures (breathing zone heights) on egress velocities and their potential effects on evacuation route design.

### 3.2 Introduction

According to the National Fire Protection Association (NFPA) [2015], most fire fatalities are caused by smoke inhalation rather than direct burns. An analysis of fire deaths between 2003 and 2007 showed that more than 80% of fire 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 building, 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 [2015d] has defined breathing zone as "… within a ten-inch 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, which may impede them from using bipedal locomotion to evacuate. In such circumstances, humans are forced to seek and adopt atypical locomotive behaviors or physical responses for survival.

According to the "Fire Evacuation Tips" from the NFPA [2015], evacuees should avoid toxic gas inhalation and access breathable air by crawling low under smoke during severe fire evacuation. Staying low under smoke also provides occupants with better vision to search for an exit route.

Only a handful of previous studies considered crawling activities in an evacuation context [Kady and Davis, 2009a; Kady and Davis, 2009b; Muhdi, Davis, and Blackburn, 2006; Nagai, Fukamachi, and Nagatani, 2006]. These studies agree that crawling causes a significant decrement in locomotive velocity. Muhdi, Davis, and Blackburn [2006] reported normal knee and hand crawling speed at 2.32 ft/s (0.71 m/s), and maximum knee and hand crawling speed at 4.82 ft/s

(1.47 m/s). Nagai, Fukamachi and Nagatani [2006] reported an average individual knee and hand crawling speed at 2.4 ft/s (0.73 m/s), which was significantly slower than the upright walking speed (3.94 ft/s (1.2 m/s)) in their study. With the exception of knee and hand crawling, no other locomotion techniques, such as foot and hand crawling or low crawling, have been reported by previous studies.

Knowing the performance capabilities and limitations of atypical locomotive behavior due to breathing zone restrictions may provide recommendations for building evacuation route designs. Current International Building Code (IBC) [2015] standards require that the distance to an exit should not exceed 250 feet. However, there is no clear evidence that humans can crawl that distance. How far and how fast humans are able to crawl in different postures has not been well studied. Accordingly, the purpose of this study was to investigate the effects of different movement postures, required by breathing zone restrictions, on locomotive velocity and maximum travel distance.

## 3.3 Method

### 3.3.1 Hypothesis

Hypothesis 1

Null Hypothesis: No difference exists among locomotive velocities using different locomotive postures.

$$H_0: V_{UW} = V_{SW} = V_{FHC} = V_{KHC} = V_{LC}$$

Alternative Hypothesis: A difference exists among locomotive velocities using different locomotive postures.

$$H_1: V_{UW} \neq V_{SW} \neq V_{FHC} \neq V_{KHC} \neq V_{LC}$$

(V: Locomotive Velocity (ft/s (m/s)), UW: Upright Walking, SW: Stoop-Walking, FHC: Foot and Hand Crawling, KHC: Knee and Hand Crawling, LC: Low Crawling)

Hypothesis 2

Null Hypothesis: No difference exists among maximum travel distances using different locomotive postures.

$$H_0: D_{UW} = D_{SW} = D_{FHC} = D_{KHC} = D_{LC}$$

Alternative Hypothesis: A difference exists among maximum travel distances using different locomotive postures.

$$H_1: D_{UW} \neq D_{SW} \neq D_{FHC} \neq D_{KHC} \neq D_{LC}$$

(D: Maximum Travel Distance (ft (m)))

### 3.3.2 Subjects

Twenty-four (24) subjects (twelve (12) males and twelve (12) females) were recruited to participate in the study. Recruitment took place among healthy college students (‘normal’ Body Mass Index (BMI): 18.5–24.9 and aged between 19 and 30) from Auburn University, AL. All subjects recruited were free of any documented musculoskeletal injuries or cardiovascular diseases.

Subject demographic data (age, height, weight and BMI) were collected (Table 3.1). This study was approved by the Auburn University Institutional Review Board (IRB) (Appendix III).

Table 3.1. Subject Demographics.

| | Age (years) | | Height (cm) | | Weight (kg) | | BMI | |
|---|---|---|---|---|---|---|---|---|
| | Male | Female | Male | Female | Male | Female | Male | Female |
| Mean | 25.67 | 24.5 | 177.75 | 164.33 | 76.5 | 56.25 | 24.21 | 20.81 |
| SD | 2.02 | 1.73 | 2.96 | 2.53 | 3.12 | 3.91 | 0.6 | 1.03 |

### 3.3.3 Postures

Five different locomotive postures were used to travel up to 300 feet (91.4 m) in the study: (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) (Figure 3.1).

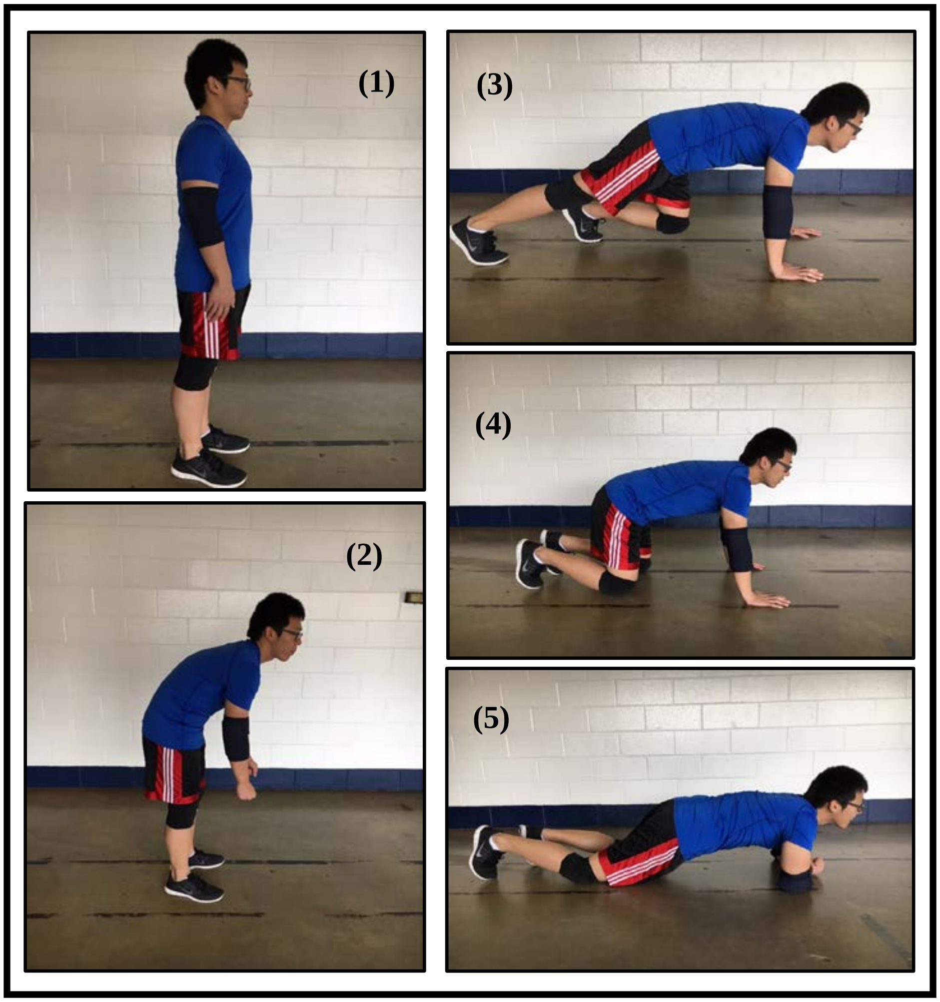


Figure 3.1. Evacuation Postures.

### 3.3.4 Equipment

A 300-foot (91.4 m) slightly curved concrete test track was established with safety cones and barriers, on the third floor of the Auburn University Coliseum. The test track was marked every thirty (30) feet (9.14m). The start and finish lines were set 10 feet (3.05m) from the beginning and the end of the track, respectively, to control 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 Heart Rate Monitor (Garmin Forerunner 110) was used to measure continuous heart rate. Knee pads, elbow pads, and gloves were provided to subjects while performing the crawling activities.

### 3.3.5 Procedure

Subjects participated in a pre-trial session which provided a chance to familiarize them with the five different locomotive postures required by the study. They were instructed to be well rested in the previous 12 hours, well hydrated, and caffeine free for at least 3 hours prior to the experiment. After subjects provided informed consent (Appendix III), each subject's age, gender, height and weight were recorded. Subjects participated in five separate trials (up to 300 feet (91.4 m) each) using different locomotive postures (UW, SW, FHC, KHC and LC) in a randomized order. An investigator closely followed each subject while pushing a cart with a digital video camera mounted to record each trial. Recorded videos were used to determine intermediate times and velocities, as subjects passed over each track section. During each trial, subjects were allowed to stop and/or request rest at any time. Subjects were provided sufficient rest to ensure that their post-trial resting heart rate returned to within 10% of their initial resting heart rate, between successive trials. All subjects were required to wear knee/elbow pads and gloves while performing the crawling activities. Stopping criteria [Dwyer and Davis, 2005] for the studies 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 predicted HR max (220-age); or stop requested by subject.

### 3.3.6 Project Analysis

Independent variables in this study were the five different locomotive postures and gender. Dependent variables were travel distance and travel velocity. Potential differences in travel velocities across the different locomotive postures were analyzed using analysis of variance (ANOVA). Post hoc tests were performed using Tukey's Honestly Significant Difference (HSD) test. Travel distances were analyzed by using survival analysis with the Kaplan-Meier estimator. Multivariate survival analyses were conducted using Cox Proportional Hazards method. Type I error rates were set at 0.05 for all statistical tests. All statistical operations and graphical analyses were performed using SAS 9.3 (Version 9.3, SAS Institute, Cary NC).

## 3.4 Results

All twenty-four (24) subjects completed the 300-foot (91.4 m) UW and SW trials. The average times for UW and SW were $49.75 \pm 11.05$ s and $52.38 \pm 11.52$ s respectively. As expected, postures affected trial completion distance. Results indicated that it was more difficult for subjects to crawl than to walk for the same distance. Only one (1) male subject completed all three 300-foot crawling (FHC, KHC, LC) trials. Table 3.2 summarizes the number of completion (# of males / # of females) and average travel distances for different postures. Reasons for not completing the entire 300-foot crawling trial in this study were voluntarily giving up or reaching 85% age-predicted Maximum Heart Rate (220-age). Survival analysis was used to detect the difference in trial completion distances among the three crawling postures. Figure 3.2 is the survival curve (completion rate curve) for three different postures as travel distance increased, calculated by the

Kaplan-Meier method. It indicated that the 250 feet (76.2 m) completion rates for FHC, KHC and LC were 4.17%, 16.67% and 8.33% respectively.

Table 3.2. Completed Trials and Average Travel Distances for Different Postures.

| | UW | SW | FHC | KHC | LC |
|---|---|---|---|---|---|
| Completed the Trial | 24 (12M/12F) | 24 (12M/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% HRmax | 0 (0M/0F) | 0 (0M/0F) | 11 (4M/7F) | 12 (3M/9F) | 14 (5M/9F) |
| Average Travel Distance ft. (m) | 300 (91.4) | 300 (91.4) | 150.21 ± 62.52 (45.78 ± 19.07) | 182.92 ± 64.02 (55.75 ± 19.51) | 172.58 ± 56.49 (52.60 ± 17.22) |

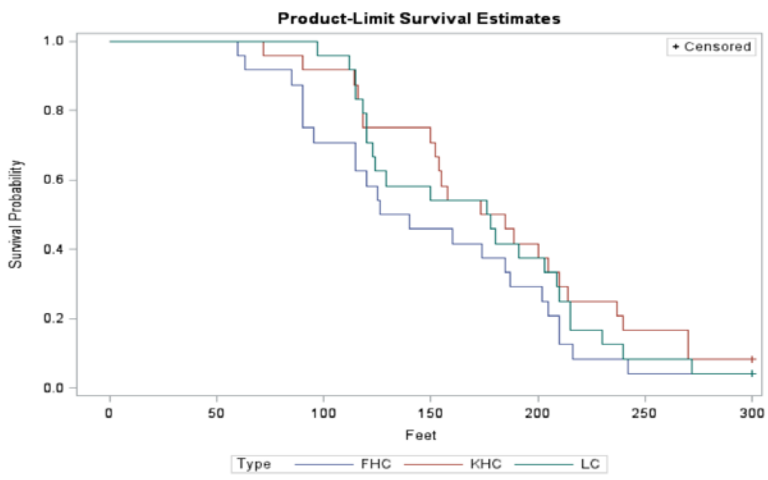


Figure 3.2. Survival Curve (Completion Rate) for Three Different Postures.

Multivariate survival analyses by Cox Proportional Hazards method indicated that the FHC completion rate per unit distance was significantly lower than LC (p=0.044, Hazard Ratio=1.841). No significant difference was detected between KHC and LC (p=0.425). Additionally, gender also showed a significant effect on trial completion distance (p<0.001). Completion rate per unit distance for female was significantly lower than completion rate for male (p<0.001, Hazard Ratio=16.95) (Table 3.3). Average crawling completion distances (FHC, KHC, LC) for male subjects were more than 200 feet, while average crawling completion distances for female subjects were less than 150 feet (Figure 3.3).

Table 3.3. Cox Proportional Hazards Regression Analysis.

| Parameter | Parameter Estimate | Chi-Square | P-Value | Hazard Ratio (HR) (95% CI for HR) |
|---|---|---|---|---|
| Gender, Female | 2.83 | 45.25 | <0.001 | 16.95 (7.431, 38.666) |
| Posture, FHC | 0.61 | 4.03 | 0.044 | 1.841 (1.015, 3.340) |
| Posture, KHC | -0.24 | 0.64 | 0.425 | 0.786 (0.435, 1.421) |

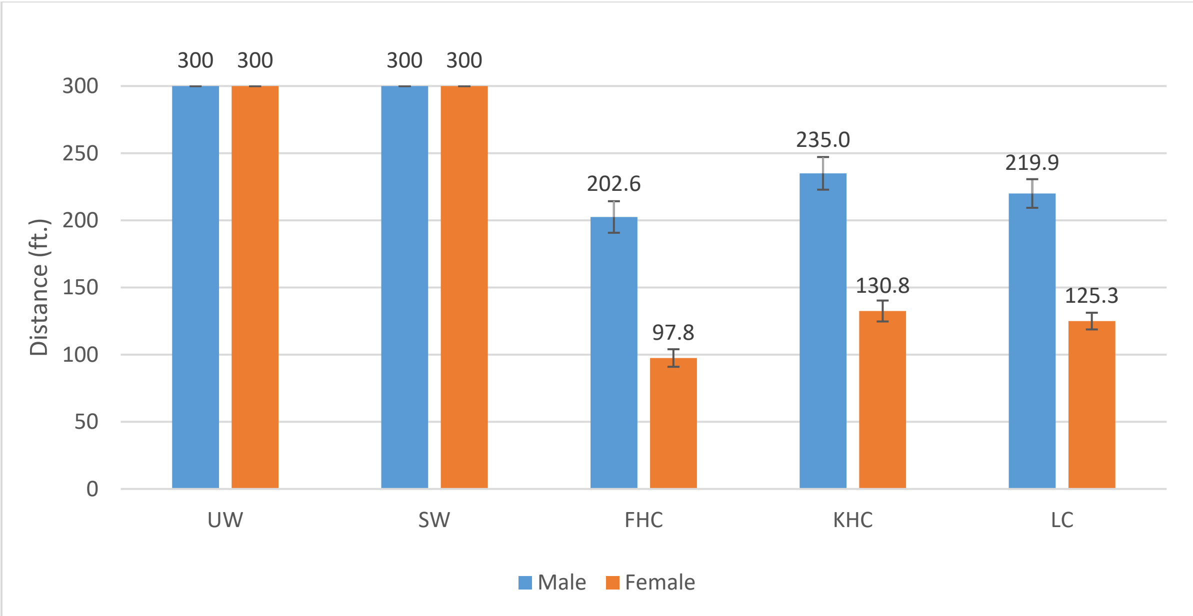


Figure 3.3. Average Travel Distances for Different Postures.

As predicted, results demonstrated that different postures affected velocities ($F_{4,88}$=132.71, p<0.001). Walking was much faster than crawling. Average UW speed in this study was measured at 6.33 ± 1.41 ft/s (1.93 ± 0.43 m/s) and average SW speed was measured at 6.04 ± 1.48 ft/s (1.84 ± 0.45 m/s). On the other hand, average travel velocities for all three types of crawling were less than 4 ft/s (1.22 m/s). Gender exhibited a significant effect on travel velocities (Figure 3.4). Males moved faster than female in UW ($F_{1,22}$=52.87, p<0.001), SW ($F_{1,22}$=17.70, p<0.001), FHC ($F_{1,22}$=53.68, p<0.001), KHC ($F_{1,22}$=57.59, p<0.001) and LC ($F_{1,22}$=43.66, p<0.001). A post hoc Tukey HSD test showed that FHC speed was significantly faster than KHC (p<0.05) and LC (p<0.05), KHC was significantly faster than LC (p<0.05). Average FHC speed was measured at 3.94 ± 0.95 ft/s (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>0.05).

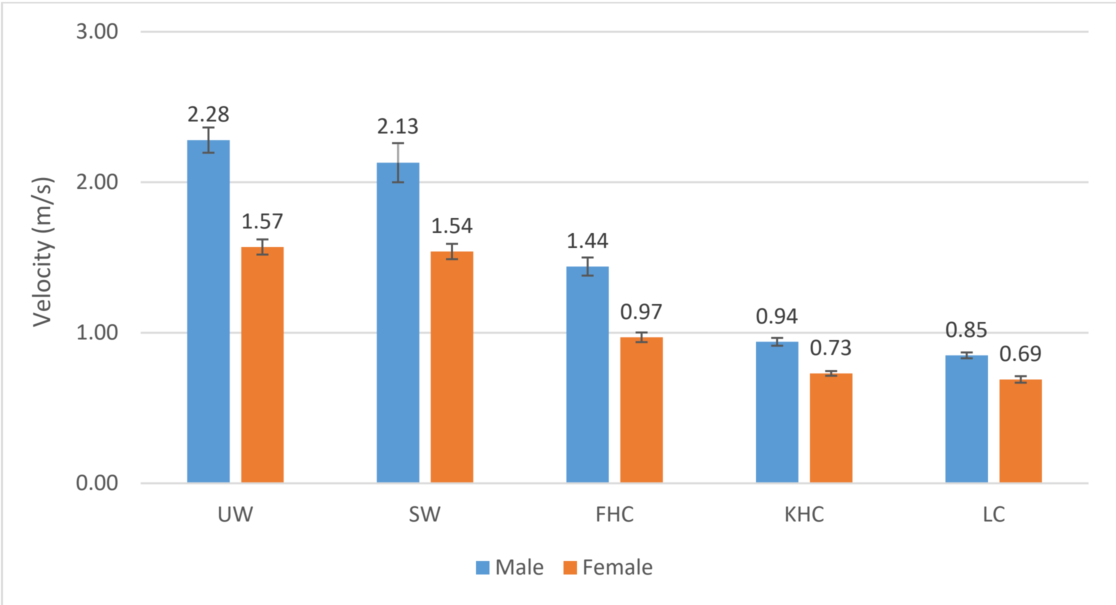


Figure 3.4. Average Travel Velocities for Different Postures.

Additionally, velocities in all crawling postures decreased significantly after the first thirty (30) feet (9.14 m) of travel. Figure 3.5 shows the average 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. No significant difference in UW velocity and SW velocity among the track sessions was detected in this study.

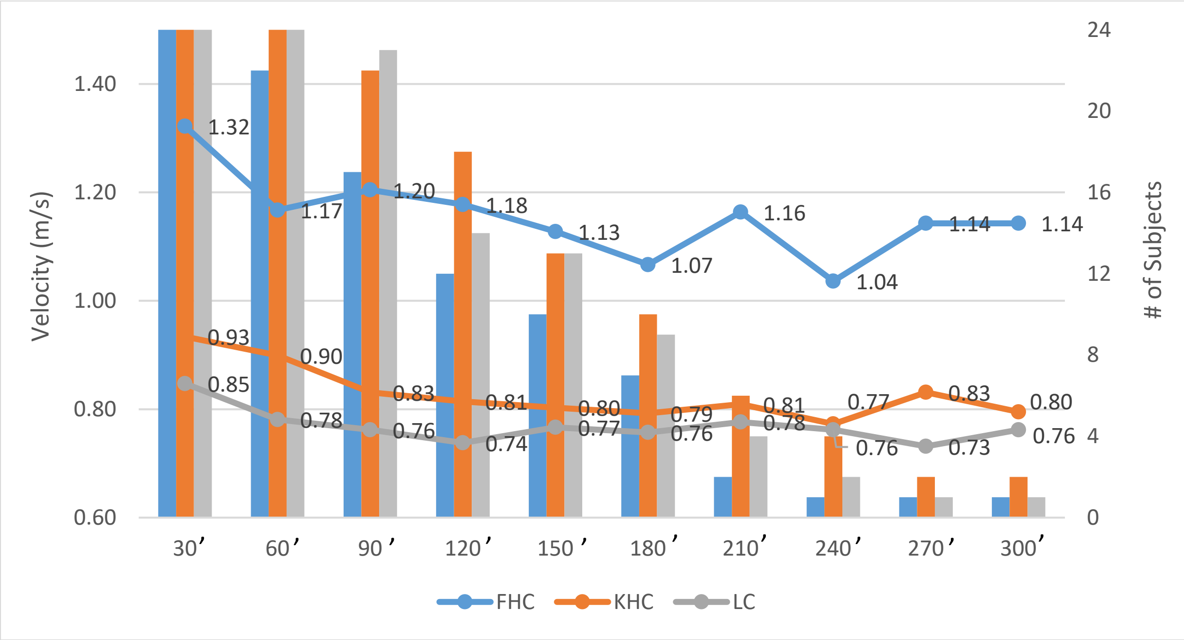


Figure 3.5. Velocities and Number of Completions for Segments.

### 3.5 Discussion

The study clearly illustrates decreased performance associated with the adoption of more restrictive locomotion postures. Average UW velocity (6.33 ft/s (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 (2.77 ft/s (0.84 m/s)) which was also similar to four-point crawling speed measured by previous crawling evacuation studies (Muhdi et al., 2006; Kady and Davis, 2009a; Kady and Davis, 2009b). Locomotion velocities during Upright Walking (UW) and Stoop-Walking (SW) were approximately twice as fast as crawling in this study.

This study considered three different crawling postures (FHC, KHC, LC) representing three different breathing zone heights. Of the three crawling postures, FHC has the advantage of higher speed compared to the other two, but FHC completion distance was significantly shorter than KHC and LC. The reason why there exist differences in travel velocity and travel distance among different crawling postures cannot be explained by this study. Further study on metabolic costs and mechanisms of different postural crawling needs to be performed.

In this study, only one (1) male subject completed all three 300-foot (91.4 m) crawling (FHC, KHC, LC) trials. 250 feet (76.2 m) completion rates for FHC, KHC and LC were 4.17%, 16.67% and 8.33% respectively. Current International Building Code (IBC) [2015] standard enforces that the distance to an exit for the building should not exceed 250 feet (76.2 m). Results of this study indicate that it is very difficult for people to crawl 250 feet (76.2 m) in optimal conditions.

It can be clearly understood by these results that a reduction in breathing zone height due to smoke in a fire 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.

Limitations of this current study are: 1) this study was conducted under normal, room-temperature conditions. Decrease in performance would likely be even greater if this study was performed under conditions with obstacles, thermal stress and limited visibility; 2) Subjects were healthy, normal BMI college students, aged from 19 to 30. Evacuation performance (locomotive velocity and travel distance) could be negatively impacted if different age groups or higher BMI subjects were tested.

## 3.6 Conclusions

The following conclusions are drawn from the current study:

1) Locomotive posture impacts human velocity. Crawling is significantly slower than walking.
2) Foot and Hand Crawling (FHC) is faster than both Knee and Hand Crawling (KHC) and Low Crawling (LC), but FHC distance is significantly shorter than KHC and LC.
3) Crawling velocities decrease significantly as travel distance increases.
4) Average maximum crawling distance is less than 250 feet (76.2 m).
5) 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.

Chapter 4

# The Effect of Locomotive Postures on Physiological Demands during Evacuation

## 4.1 Abstract

Depending on the circumstances, crawling maybe essential to evacuate from a burning building to avoid toxic gas inhalation and access breathable air. Few studies have evaluated physiological implications while crawling. Those that have been completed generally agree that crawling places high physical demands on the body. Therefore, the purpose of this study was to investigate the metabolic costs of atypical postural locomotion during evacuation. Twenty-four (24) healthy college students (12 males and 12 females), aged from 19 to 30, participated in this study to travel up to 300 feet (91.4m) in five different postures: Upright Walking (UW), Stoop-Walking (SW), Foot and Hand Crawling (FHC), Knee and Hand Crawling (KHC), and Low Crawling (LC). Results of the study demonstrated that crawling was more physically demanding than walking, represented by higher Heart Rates (HR) levels, higher Volumes of Oxygen consumption ($VO_2$), higher Ventilation Rates ($V_E$) and higher Respiratory Exchange Ratios (RER). Additionally, crawling was perceived by subjects to be much more difficult than walking. Understanding the metabolic costs of atypical postural locomotion provides a way to evaluate human capabilities and limitations during evacuation and potentially impacts evacuation route design.

## 4.2 Introduction

One of the most crucial aspects of building fire safety is the potential of safe evacuation. Evacuation velocity and travel distance, certainly are the most important factors to predict the successfulness of an evacuation and to estimate the total required evacuation time to reach an exit. Chapter Three of this dissertation reported significant differences in evacuation velocity and travel distance between the different locomotive techniques. However, the reason why atypical postures cause a significant decrement in evacuation velocity and travel distance has not been well studied. One reasonable interpretation for this could be the high physical demand of atypical postural locomotion. Little research has examined the physiological effects of atypical locomotion on evacuees. Previous studies that investigated the physiological demands of bipedal activities (walking, jogging or running) agreed that walking was much less physiologically demanding than other bipedal locomotive techniques [Walt and Wyndham, 1973; Dill, 1965; Flynn et al., 1994; Francis and Hoobler, 1986; Jones, Toner, Daniels, and Knapik, 1984; Fudge et al., 2007]. Volumes of oxygen consumption for walking in most previous studies were reported as approximately 20 mL/(kg·min) and average heart rates were measured at approximately 100 bpm [Walt and Wyndham, 1973; Dill, 1965; Jones et al., 1984; Mattsson et al., 1997; Martin et al., 1992]. Compared to the studies on metabolic costs of bipedal activities, relatively little research has considered physiological demands of atypical postural locomotion (e.g., crawling). The available literature suggests that crawling results in significant physiological demands as well as physical discomfort [Moss, 1934]. Gallagher, et al. [2011] found significant differences in locomotion performance and physiological demands among stoop-walking, 2-point crawling (using both knees), and 4-point crawling (using hands and knees), when moving in restricted spaces. Average heart rate for 4-point crawling measured in their study was significantly higher than stoop-walking and 2-point 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 hand and knee crawling activities. Davis [2011] conducted this study on a treadmill and evaluated the Heart Rates (HR), Volumes of Oxygen consumption ($VO_2$), Ventilation Rates ($V_E$) and Ratings of Perceived Exertion (RPE) for crawling and walking. Results indicated that HRavg in the crawling trial was significantly higher (63.8 bpm higher) than in the walking trial, average $VO_2$ in the crawling trial was significantly higher (10.8 mL/(kg·min) higher) than in the walking trial and average $V_E$ in the crawling trial was significantly higher (33.47 L/min higher) than in the walking trial.

However, only metabolic costs of stoop-walking and knee and hand crawling were investigated in previous studies, other locomotive postures (e.g., foot and hand crawling, low crawling) that may be used during evacuation were not studied. Knowing the metabolic costs of different types of locomotion helps to estimate physiological demands during evacuation, which provides a way to evaluate human evacuation performance (e.g., how far are evacuees able to crawl during emergency evacuations). Accordingly, the purpose of this study was to investigate the effects of different locomotive postures on physiological demands.

## 4.3 Method

### 4.3.1 Hypothesis:

Hypothesis 1:

Null Hypothesis: No difference exists among Average Heart Rates using different locomotive postures.

$$H_0: HR_{UW} = HR_{SW} = HR_{FHC} = HR_{KHC} = HR_{LC}$$

Alternative Hypothesis: A difference exists among Average Heart Rates using different locomotive postures.

$$H_1: HR_{UW} \neq HR_{SW} \neq HR_{FHC} \neq HR_{KHC} \neq HR_{LC}$$

(HR: Average Heart Rate (bpm), UW: Upright Walking, SW: Stoop-Walking, FHC: Foot and Hand Crawling, KHC: Knee and Hand Crawling, LC: Low Crawling)

Hypothesis 2:

Null Hypothesis: No difference exists among Volumes of Oxygen consumption using different locomotive postures.

$$H_0: VO_{2\,UW} = VO_{2\,SW} = VO_{2\,FHC} = VO_{2\,KHC} = VO_{2\,LC}$$

Alternative Hypothesis: A difference exists among Volumes of Oxygen consumption using different locomotive postures.

$$H_1: VO_{2\,UW} \neq VO_{2\,SW} \neq VO_{2\,FHC} \neq VO_{2\,KHC} \neq VO_{2\,LC}$$

($VO_2$: Volume of Oxygen consumption (mL/(kg·min))

Hypothesis 3:

Null Hypothesis: No difference exists among Ventilation Rates using different locomotive postures.

$$H_0: V_{E\,UW} = V_{E\,SW} = V_{E\,FHC} = V_{E\,KHC} = V_{E\,LC}$$

Alternative Hypothesis: A difference exists among Ventilation Rates using different locomotive postures.

$$H_1: V_{E\,UW} \neq V_{E\,SW} \neq V_{E\,FHC} \neq V_{E\,KHC} \neq V_{E\,LC}$$

($V_E$: Ventilation Rate (L/min))

Hypothesis 4:

Null Hypothesis: No difference exists among Respiratory Exchange Ratios using different locomotive postures.

$$H_0: RER_{UW} = RER_{SW} = RER_{FHC} = RER_{KHC} = RER_{LC}$$

Alternative Hypothesis: A difference exists among Respiratory Exchange Ratios using different locomotive postures.

$$H_1: RER_{UW} \neq RER_{SW} \neq RER_{FHC} \neq RER_{KHC} \neq RER_{LC}$$

(RER: Respiratory Exchange Ratio)

Hypothesis 5:

Null Hypothesis: No difference exists among Ratings of Perceived Exertion using different locomotive postures.

$$H_0: RPE_{UW} = RPE_{SW} = RPE_{FHC} = RPE_{KHC} = RPE_{LC}$$

Alternative Hypothesis: A difference exists among Ratings of Perceived Exertion using different locomotive postures.

$$H_1: RPE_{UW} \neq RPE_{SW} \neq RPE_{FHC} \neq RPE_{KHC} \neq RPE_{LC}$$

(RPE: Rating of Perceived Exertion)

### 4.3.2 Subjects

Twenty-four (24) subjects (twelve (12) males and twelve (12) females) were recruited to participate in the study. Recruitment took place among healthy college students ('normal' Body Mass Index (BMI): 18.5–24.9 and aged between 19 and 30) from Auburn University, AL. All subjects recruited were free of any documented musculoskeletal injuries or cardiovascular diseases. Subject demographic data (age, height, weight and BMI) were collected (Table 4.1). This study was approved by the Auburn University Institutional Review Board (IRB) (Appendix III).

Table 4.1. Subject Demographics.

| | Age (years) | | Height (cm) | | Weight (kg) | | BMI | |
|---|---|---|---|---|---|---|---|---|
| | Male | Female | Male | Female | Male | Female | Male | Female |
| Mean | 25.67 | 24.5 | 177.75 | 164.33 | 76.5 | 56.25 | 24.21 | 20.81 |
| SD | 2.02 | 1.73 | 2.96 | 2.53 | 3.12 | 3.91 | 0.6 | 1.03 |

### 4.3.3 Postures

Five different locomotive postures were used in this study: Upright Walking (UW), Stoop-Walking (SW), Foot and Hand Crawling (FHC), Knee and Hand Crawling (KHC), and Low Crawling (LC).

### 4.3.4 Equipment

A 300-foot (91.4m) slightly curved concrete test track was established with safety cones and barriers, on the third floor of Auburn University Coliseum. The test track was marked every thirty (30) feet (9.14m). The start and finish lines were set 10 feet (3.05m) from the beginning and the end of the track, respectively, to control any acceleration or deceleration effects. A digital video camera (Canon FS300) was mounted on a wheeled cart which followed subjects to record their movement. The COSMED K4b2 (a portable system for pulmonary gas exchange measurement) was used to measure Volumes of Oxygen consumption ($VO_2$), Ventilation Rates ($V_E$) and Respiratory Exchange Ratios (RER) when subjects were performing the study. A Heart Rate Monitor (Garmin Forerunner 110) was used to measure continuous Heart Rate (HR). Knee pads, elbow pads, and gloves were provided to subjects while performing the crawling activities.

### 4.3.5 Procedure

Subjects participated in a pre-trial session which provided a chance to familiarize them with the five different locomotive postures used in the study. They were instructed to be well rested in the previous 12 hours, well hydrated, and caffeine free for at least 3 hours prior to the experiment. After subjects provided informed consent (Appendix III), each subject's age, gender, height and weight were recorded.

Subjects were instrumented with a COSMED K4b2 unit (~ 5 pounds total). They were asked to wear a COSMED k4b2 face mask to record respiratory response and a heart rate monitor to record resting and locomotive heart rates. The COSMED k4b2 was calibrated before each test. Subjects' initial Volumes of Oxygen consumption ($VO_2$) and Resting Heart Rates (HRrest) were recorded before starting any tests. Subjects were instructed to perform five separate trials (up to 300 feet (91.4 m) each) using different locomotive postures (UW, SW, KHC, FHC and LC) in a randomized order. An investigator closely followed each subject, while pushing a cart with a digital video camera mounted to record the entire of each trial (Figure 4.1).

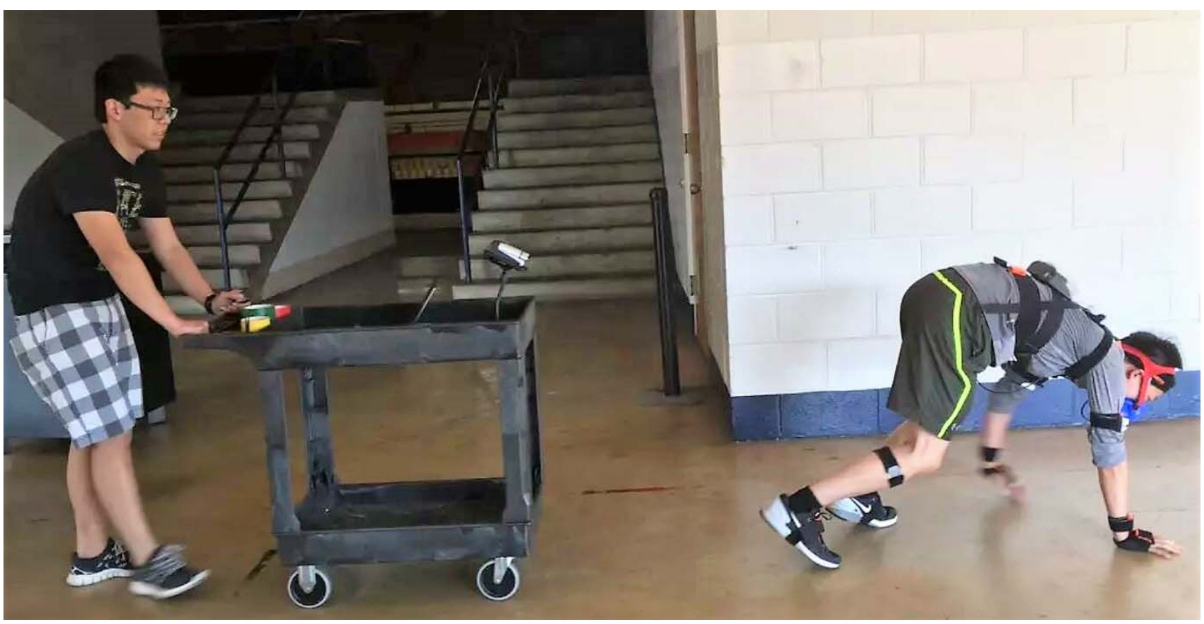

Figure 4.1. Digital Camera to Record the Entire Trial.

During each trial, subjects were allowed to stop and/or request rest at any time. Subjects were provided sufficient rest to ensure that their post-trial Resting Heart Rates (HRrest) returned to within 10% of their initial Resting Heart Rates (HRrest), between successive trials. Subjects were asked to report their Ratings of Perceived Exertion (RPE) after each trial. All subjects were required to wear knee/elbow pads and gloves while performing the crawling activities. Stopping criteria [Dwyer and Davis, 2005] for the studies 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 predicted Maximum Heart Rate (HRmax) (220-age); or stop requested by subject.

#### 4.3.6 Project Analysis

Independent variables in this study were the five different locomotive postures and gender. Dependent variables included Volume of Oxygen consumption ($VO_2$), Ventilation Rate ($V_E$), Respiratory Exchange Ratio (RER), Heart Rate (HR) and Rating of Perceived Exertion (RPE). Potential differences in $VO_2$, $V_E$, RER, HR and RPE across the different locomotive postures were analyzed using analysis of variance (ANOVA). Post hoc tests were performed using Tukey's Honestly Significant Difference (HSD) test. Type I error rates were set at 0.05 for all statistical tests.

### 4.4 Results

All twenty-four (24) subjects completed 300-foot (91.4 m) UW and SW trials in under 1 minute and 20 seconds. Only one subject completed all three crawling trials. Over the entire study, the average time for crawling trials was under 1 minute. Results indicated that locomotive postures had a significant effect on physiological demands. Average Heart Rate (HRavg) was significantly affected by locomotive postures ($F_{4,88}$= 115.41, $p<0.001$). During UW and SW, subject's Heart Rate (HR) slightly increased as walking proceeded and subject's Heart Rate (HR) never reached 70% of their age-predicted Maximum Heart Rate (HRmax). Conversely in the three crawling trials, individual Heart Rate (HR), Volume of Oxygen consumption ($VO_2$), Ventilation Rate ($V_E$) and Respiratory Exchange Ratio (RER) dramatically increased after crawling for approximately 20 seconds. All subjects reached 70% of their age-predicted Maximum Heart Rate (HRmax) during the crawling trials. Most subjects reached their 70% of HRmax between 25 seconds and 40 seconds of crawling (Figure 4.2). According to the American College of Sports Medicine (ACSM) [2007], during low-intensity physical activities, a person's heart rate will be below 50% of maximum heart rate. During moderate-intensity physical activity, a person's heart rate will be around 50% to 70% of maximum heart rate, and during high-intensity physical activity, a person's heart rate will be around 70% to 85% of maximum heart rate. In this study, the test was stopped immediately if the subject reached 85% of his/her age-predicted Maximum Heart Rate (HRmax). ACSM has defined two stopping criteria for submaximal tests. The first criterion is if subjects' maximum heart rate reaches 85% of their age-predicted maximum heart rate. The second criterion is if subjects reach 70% of their age-predicted Heart Rate Reserve (HRreserve) [Dwyer and Davis, 2005]. Average 70% of age-predicted Heart Rate Reserve (HRreserve) in this study was calculated at 161.35 ± 3.01 bpm, which was slightly lower than 85% of age-predicted Maximum Heart Rate (HRmax)

(165.68 ± 1.64). Table 4.2 shows the number of subjects that reached 85% of their age-predicted Maximum Heart Rate (HRmax) and the number of subjects that reached 70% of their age-predicted Heart Rate Reserve (HRreserve). Figure 4.3 is an example of subject heart rate responses in five different locomotive postures. This subject's 70% HRreserve (162 bpm) and 85% HRmax (168.3 bpm) are also shown in Figure 4.3.

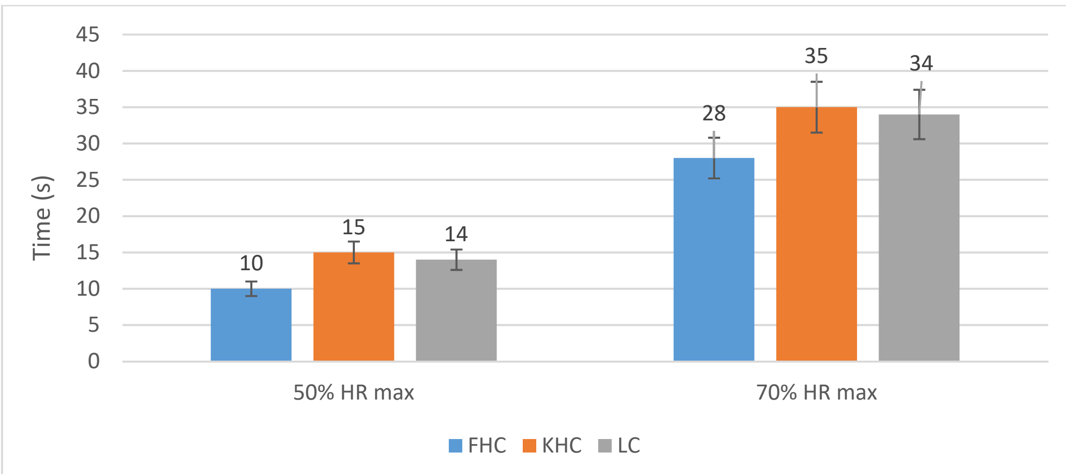


Figure 4.2. Average Travel Time to Reach 50% HRmax and 70% HRmax.

Table 4.2. Subjects Reaching 85% HRmax or 70% HRreserve.

| | UW | SW | FHC | KHC | LC |
|---|---|---|---|---|---|
| Reached 85% HRmax | 0 (0M/0F) | 0 (0M/0F) | 11 (4M/7F) | 12 (3M/9F) | 14 (5M/9F) |
| Reached 70% HRreserve | 0 (0M/0F) | 0 (0M/0F) | 14 (6M/8F) | 14 (5M/9F) | 14 (5M/9F) |

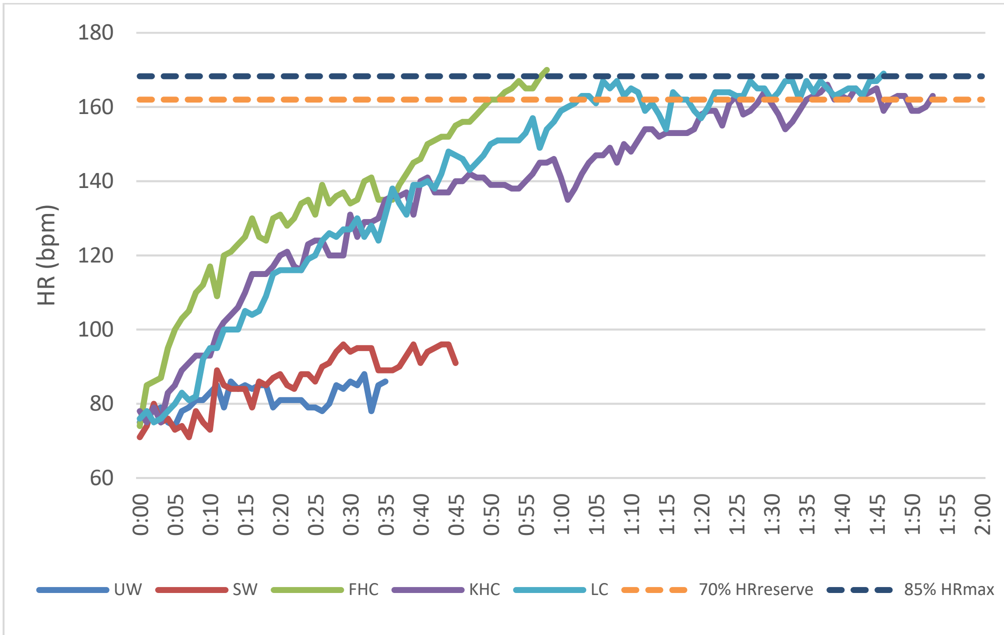


Figure 4.3. Example of Subject Heart Rate Responses.

Figure 4.4 shows heart rate responses for different locomotion methods. It should be noted that the Average Heart Rate (HRavg) for each time point in Figure 4.4 was based on the remaining subjects. A post hoc Tukey HSD test indicated that the Average Heart Rate (HRavg) during FHC was significantly higher than the Average Heart Rates (HRavg) during KHC ($p<0.05$) and LC ($p<0.05$). On the other hand, the Average Heart Rates (HRavg) during KHC and LC were not significantly different ($p>0.05$). The Average Heart Rates (HRavg) for UW and SW in this study were 92 bpm and 93 bpm respectively, while Average Heart Rates (HRavg) for FHC, KHC and LC were 134 bpm, 128 bpm and 130 bpm, respectively.

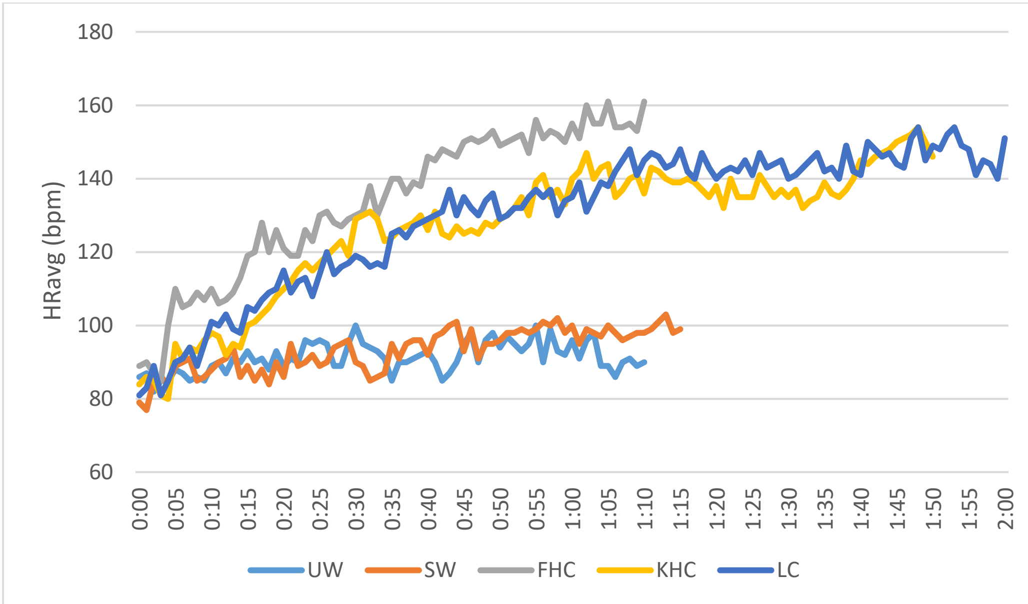


Figure 4.4. Average Heart Rates (HRavg).

Additionally, locomotive postures also significantly affected the amount of time that subjects required to return to their Resting Heart Rate (HRrest) ($F_{4,88}$= 93.54, p<0.001). It took significantly longer for subjects to return to their Resting Heart Rate (HRrest) after crawling compared to walking (Figure 4.5). A post hoc Tukey HSD test showed that time to return to Resting Heart Rate (HRrest) after FHC was significantly longer than time to return to Resting Heart Rate (HRrest) after KHC (p<0.05) and LC (p<0.05). On average, it took subject 9 minutes and 16 seconds to return to Resting Heart Rate (HRrest) after FHC. No significant difference was detected between KHC and LC (p>0.05).

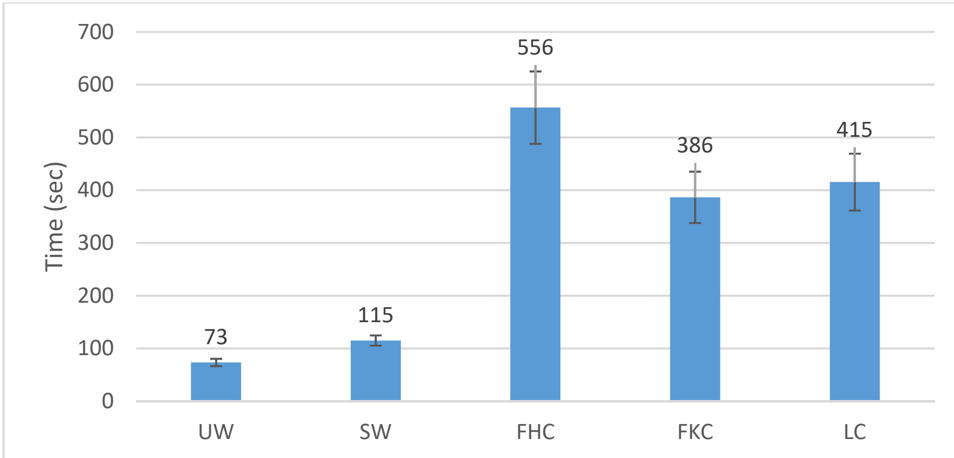


Figure 4.5. Time to Return to Resting Heart Rate (HRrest).

Figure 4.6 and Figure 4.7 show the Volumes of Oxygen consumption ($VO_2$) and Ventilation Rates ($V_E$) during different types of locomotion. The average $VO_2$ and $V_E$ for each time point in Figure 4.6 and Figure 4.7 were based on the remaining subjects. Locomotive postures significantly affected $VO_2$ ($F_{4,88}$=89.1, $p<0.001$) and $V_E$ ($F_{4,88}$=103.5, $p<0.001$). Volumes of Oxygen consumption ($VO_2$) were significantly higher in the crawling trials than in the walking trials ($p<0.05$). Ventilation Rates ($V_E$) exhibited a similar trend as Volumes of Oxygen consumption ($VO_2$) in this study. On average, Ventilation Rates ($V_E$) during the FHC trials were 51.12 L/min higher than the UW trials, Volumes of Oxygen consumption ($VO_2$) during FHC were 28.10 mL/(kg·min) higher than the UW trials. However, a statistically significant gender effect on $VO_2$ and $V_E$ was not detected.

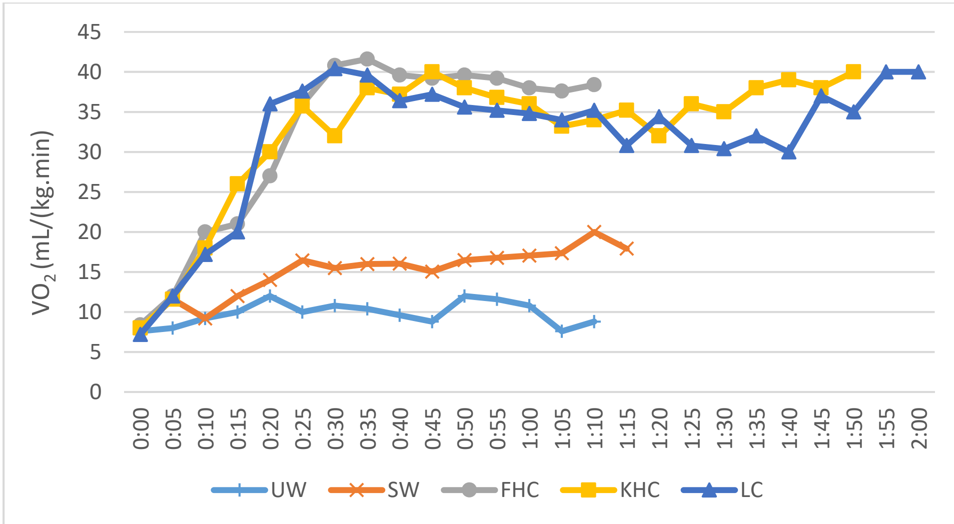


Figure 4.6. Average Volumes of Oxygen Consumption ($VO_2$).

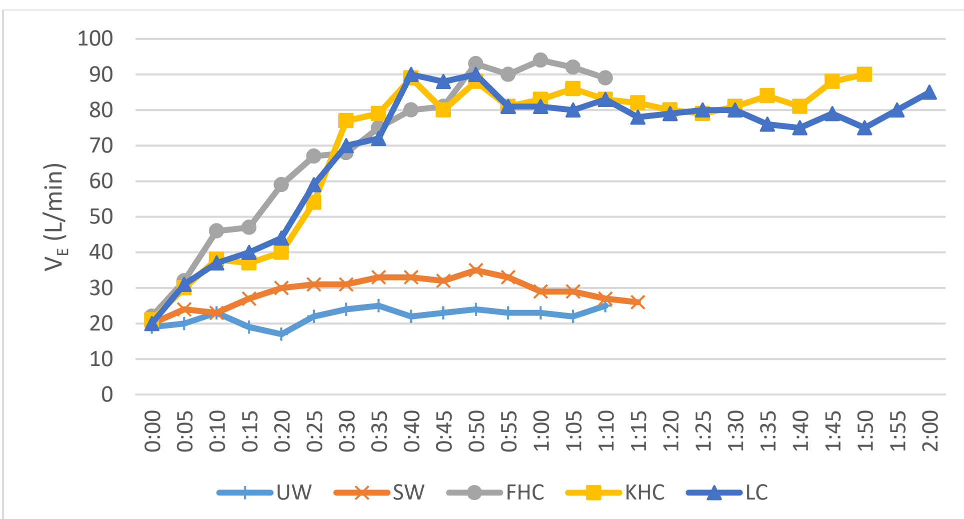


Figure 4.7. Average Ventilation Rates ($V_E$).

Average Respiratory Exchange Ratios (RER) for FHC, KHC and LC in this study were measured at 1.09 ± 0.09, 1.05 ± 0.1 and 1.06 ± 0.05 respectively. Average RER during walking trials measured in this study were lower than 0.9. RER is the ratio of Volume of Carbon Dioxide production to Volume of Oxygen consumption ($VCO_2/VO_2$). According to the 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 any significant effect on RER during crawling trials.

The Ratings of Perceived Exertion (RPE) (0 – 10) also displayed a much higher response in the crawling trials compared to the walking trials. FHC, with an average rating of 8.13 ± 0.53, was perceived to be more difficult than other crawling techniques (Figure 4.8). Figure 4.9 and Figure 4.10 show subjects' Ratings of Perceived Exertion (RPE) for different postures.

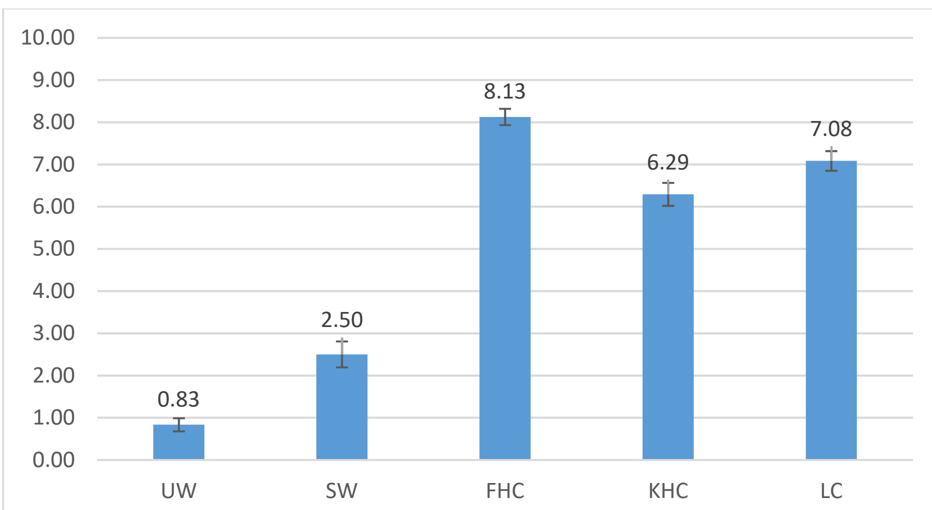


Figure 4.8. Average Ratings of Perceived Exertion (RPE) for Different Postures.

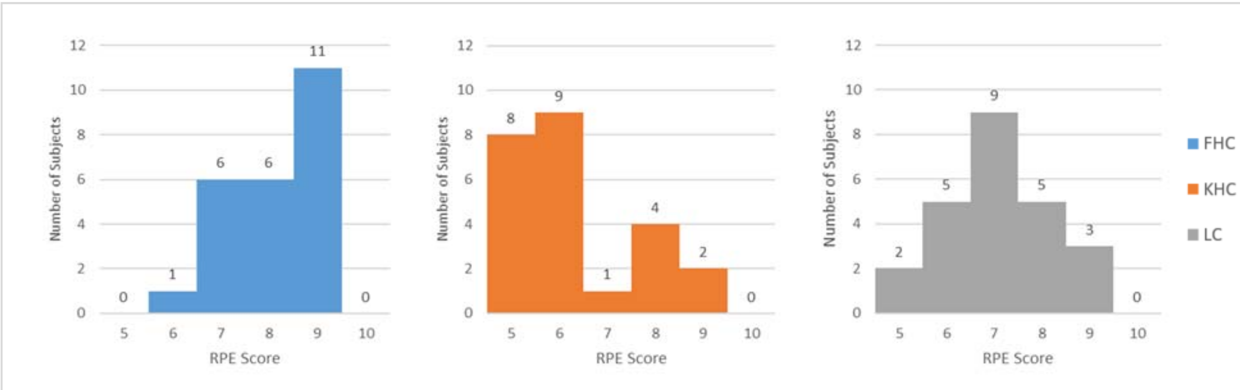


Figure 4.9. Ratings of Perceived Exertion (RPE) for FHC, KHC and LC.

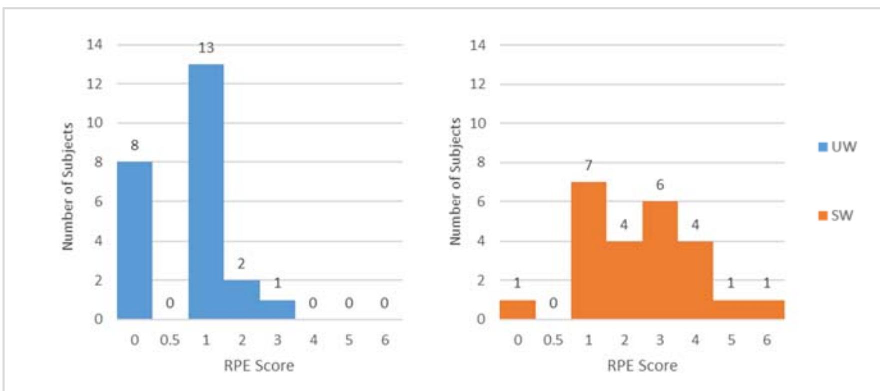


Figure 4.10. Ratings of Perceived Exertion (RPE) for UW and SW.

## 4.5 Discussion

The purpose of this study was to investigate the physiological demands of atypical postural locomotion during evacuation. 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 breathing zone heights during evacuation. All dependent variables (HR, $VO_2$, $V_E$, RER and RPE) in this study were significantly different between postural types. Crawling was more physically demanding than walking, represented by higher Average Heart Rate (HRavg) levels, higher Volumes of Oxygen consumption ($VO_2$), higher Ventilation Rates ($V_E$) and higher Respiratory Exchange Ratios (RER). Physiological demands of UW and KHC found in this study were similar to those reported in previous crawling studies [Morrissey et al., 1985; Gallagher et al., 2011; Davis, 2011]. The Average Heart Rate (HRavg) for crawling was approximately 71% higher than walking and the average Volume of Oxygen consumption ($VO_2$) for crawling was approximately 87% higher than walking. For all three crawling (FHC, KHC and LC) tasks, individual Heart Rates (HR) and Volumes of Oxygen consumption ($VO_2$) dramatically increased after crawling for approximately 20 seconds. All subjects reached their 70% Maximum Heart Rate (HRmax) during crawling and 14 of 24 subjects were forced to stop crawling due to reaching 85% of their Maximum Heart Rate (HRmax). However, in UW and SW tasks, no subject reached 70% Maximum Heart Rate (HRmax). According to the American College of Sports Medicine (ACSM) [2007], during low-intensity physical activities, a person’s heart rate will stay below 50% of maximum heart rate. During moderate-intensity physical activity, a person’s heart rate will be around 50% to 70% of maximum heart rate. During high-intensity physical activity, a person's heart rate will be around 70% to 85% of maximum heart rate. Heart rate responses recorded in this study indicates that crawling is a high-intensity activity. Ventilation Rate ($V_E$) is the total volume of air entering the lungs per minute. As expected, Ventilation Rate ($V_E$) exhibited a similar pattern as Heart Rate (HR) and Volume of Oxygen consumption ($VO_2$) in this study.

The Respiratory Exchange Ratio (RER) is the ratio between the amount of Carbon Dioxide ($CO_2$) produced and Oxygen ($O_2$) uptake. Previous research indicated that the Respiratory

Exchange Ratio (RER) increased with exercise intensity. Respiratory Exchange Ratio (RER) is around 0.8 at rest and can exceed 1.0 during intense exercise. A high Respiratory Exchange Ratio (RER) indicates that carbohydrates are being predominantly used, whereas a low Respiratory Exchange Ratio (RER) suggests lipid oxidation [Simonson and DeFronzo, 1990]. Average Respiratory Exchange Ratios (RER) for FHC, KHC and LC in this study are larger than 1.0 and very close to 1.1, which suggests that crawling is a 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 the firefighters' physiological demands when performing firefighting or rescuing [Barnard and Duncan, 1975; Sothmann et al., 1990; Davis and Gallagher, 2014; Davis, Tang and Sesek, 2014]. Physiological demands during crawling measured in the present study are similar to previous firefighting research.

Sothmann et al. [1990], studied twenty (20) firefighters while monitoring Heart Rate (HR), Volume of Oxygen consumption ($VO_2$), and Ventilation Rate ($V_E$) 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 at a duration ranging from 14.4 min to 21.0 min. They found that the maximum heart rate during crawling averaged 174 bpm, about 97 bpm higher than their resting heart rate. The volume of air consumed from the SCBA's averaged at 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.

In addition, crawling was perceived to be more difficult than walking in this study. All subjects rated FHC as the most difficult posture to perform among all five postures when considering the Rating of Perceived Exertion (RPE). During a post-experiment interview, one subject mentioned that FHC was like a 'traveling plank', which was very hard to maintain balance and to keep one's head up at all times. The reason why FHC is more physically demanding than other locomotive postures has not been fully investigated in this study. Further study on the kinematics of the different locomotive postures should be performed.

Limitations of this current study include: 1) 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 demand during evacuation could be impacted if different age groups or higher BMI subjects were tested. 2) subjects were instrumented with a COSMED K4b2 unit (~ 5 pounds in total) and a face mask to record their respiratory responses. COSMED K4b2 unit and respiratory face mask could negatively impact (discomfort, vision degradation, etc.) movement.

### 4.6 Conclusions

The following conclusions are drawn from the current study:

1) Different locomotive postures cause significant differences in physiological demands during evacuation. Crawling is more physically demanding than walking, represented by higher Average Heart Rate (HRavg) levels, higher Volumes of Oxygen consumption ($VO_2$), higher Ventilation Rates ($V_E$), and higher Respiratory Exchange Ratios (RER).

2) Individual Heart Rate (HR), Volume of Oxygen consumption ($VO_2$), Ventilation Rate ($V_E$) and Respiratory Exchange Ratio (RER) dramatically increase after crawling for approximately 20 seconds.
3) Crawling is an intense activity (RER>1.0) that takes subjects more time to recover compared to walking.
4) Crawling is perceived to be more physically demanding than walking on an identical course. Foot and Hand Crawling (FHC) is perceived to be the most difficult crawling technique.
5) Gender has no significant effect on Heart Rate (HR), Volume of Oxygen consumption ($VO_2$), Ventilation Rate ($V_E$), and Respiratory Exchange Ratio (RER) during crawling.

Chapter 5

# Kinematic Analysis of Different Locomotive Postures

## 5.1 Abstract

In severe fire conditions, humans are forced to seek and adopt atypical locomotive behaviors or physical responses for survival. A thorough understanding of human crawling behavior remains incomplete. Accordingly, this study focused on the kinematic analysis of different locomotive postures. Twenty-four (24) subjects (12 males and 12 females, aged 19-30 years) were recruited in this study to travel up to 300 feet (91.4 m) using five different locomotive postures. A 3D motion tracking system, Xsens, was used to collect kinematic data including stride duration, stride length, interlimb coordination patterns, and points of contact to the ground. Results indicated that Knee and Hand Crawling (KHC) had a shorter step cycle than Foot and Hand Crawling (FHC) ($p<0.05$) and Low Crawling (LC) ($p<0.05$). Males tended to have a longer stride than females in Upright Walking (UW) ($p<0.05$), Stoop-Walking (SW) ($p<0.05$), Foot and Hand Crawling (FHC) ($p<0.05$), and Low Crawling (LC) ($p<0.05$). Results of this study demonstrated that limb coordination patterns were much more consistent during the first 50 feet (15.2 m) of crawling and subjects maintained two-point contact (diagonal limbs) to the ground for the most of time during the first 50 feet (15.2 m) of crawling. Results of this study provide kinematic implications for different locomotive postures and potential recommendations for crawling strategies.

## 5.2 Introduction

In fire emergencies, upright walking may not be a viable gait option for occupants to evacuate. Humans may need to adopt atypical locomotive postures and different physical responses for successful evacuation. A few evacuation studies have examined atypical locomotive behaviors during evacuation. However, most of those studies only reported the crawling evacuation velocity. Kinematics of atypical postural locomotion has not been thoroughly investigated.

Several non-evacuation studies detected the interlimb coordination patterns for knee crawling, knee and hand crawling and foot and hand crawling [Gallagher et al., 2011; Babic et al., 2001; Wannier et al., 2001; Patrick et al., 2009; MacLellan et al., 2012]. Patrick et al. [2009] performed a study to examine the interlimb coordination patterns for a hand-knee crawling task. Interlimb coordination patterns were assessed and quantified by the Ipsilateral Phase Lag (IPL). Patrick et al. [2009] defined the IPL as the delay between the stance phase of the left arm and the stance phase of the left leg. They pointed out that IPL close to 50% indicated that limbs enter stance alternately, which was defined as a "trot-like" gait. IPL close to 0% or 100% indicated a "pace-like" gait, in which ipsilateral limbs contacted the ground around the same time, while IPL values between "pace-like" and "trot-like" indicated "no pairing of limbs", with the four limbs entering stance equally spaced in time.

A study by Babic et al. [2001] assessed the gait patterns of hand-knee crawling in three different speed levels. Results indicated that as speed increased, crawling tended to change from three or four-point stance phases to two-point stance phases (one hand and contralateral knee were on the ground), which led to a dynamically unstable state. In addition, a study by MacLellan et al. [2012] investigated hand-foot crawling behavior and indicated that the number of limbs (four, three, or two) supporting the whole-body weight was dependent on the speed and the instant of the gait cycle. In their study, a "trot-like" pattern (IPL close to 50%) and a "pace-like" pattern (IPL close to 0%) were observed in foot and hand crawling and these patterns did not change among different crawling speeds.

However, except for knee and hand crawling and foot and hand crawling, no other postures have been further studied. Most kinematic analyses of crawling are neuroscience related [Babic et al., 2001; Wannier et al., 2001; Patrick et al., 2009;]. None of those kinematic analyses were conducted in an evacuation context. This study focused on the kinematic analysis of different locomotive postures during evacuation, including Upright Walking (UW), Stoop-Walking (SW), Knee and Hand Crawling (KHC), Foot and Hand Crawling (FHC), and Low Crawling (LC).

## 5.3 Method

### 5.3.1 Hypothesis

Hypothesis 1

Null Hypothesis: No difference exists among Step Cycle Times using different locomotive postures.

$$H_0: SCT_{UW} = SCT_{SW} = SCT_{FHC} = SCT_{KHC} = SCT_{LC}$$

Alternative Hypothesis: A difference exists among Step Cycle Times using different locomotive postures.

$$H_1: SCT_{UW} \neq SCT_{SW} \neq SCT_{FHC} \neq SCT_{KHC} \neq SCT_{LC}$$

(SCT: Step Cycle Time (s/cycle), UW: Upright Walking, SW: Stoop-Walking, FHC: Foot and Hand Crawling, KHC: Knee and Hand Crawling, LC: Low Crawling)

Hypothesis 2

Null Hypothesis: No difference exists among Stride Lengths using different locomotive postures.

$$H_0: SL_{UW} = SL_{SW} = SL_{FHC} = SL_{KHC} = SL_{LC}$$

Alternative Hypothesis: A difference exists among Stride Lengths using different locomotive postures.

$$H_1: SL_{UW} \neq SL_{SW} \neq SL_{FHC} \neq SL_{KHC} \neq SL_{LC}$$

(SL: Stride Length (ft))

Hypothesis 3

Null Hypothesis: No difference exists among Interlimb Coordination Patterns using different locomotive postures.

$$H_0: ICP_{UW} = ICP_{SW} = ICP_{FHC} = ICP_{KHC} = ICP_{LC}$$

Alternative Hypothesis: A difference exists among Interlimb Coordination Patterns using different locomotive postures.

$$H_1: ICP_{UW} \neq ICP_{SW} \neq ICP_{FHC} \neq ICP_{KHC} \neq ICP_{LC}$$

(ICP: Interlimb Coordination Pattern)

Hypothesis 4

Null Hypothesis: No difference exists among Points of Contact to the Ground using different locomotive postures.

$$H_0: PC_{UW} = PC_{SW} = PC_{FHC} = PC_{KHC} = PC_{LC}$$

Alternative Hypothesis: A difference exists among Points of Contact to the Ground using different locomotive postures.

$$H_1: PC_{UW} \neq PC_{SW} \neq PC_{FHC} \neq PC_{KHC} \neq PC_{LC}$$

(PC: Points of Contact to the Ground)

### 5.3.2 Subjects

Twenty-four (24) subjects (twelve (12) males and twelve (12) females) were recruited to participate in the study. Recruitment took place among healthy college students (‘normal’ Body Mass Index (BMI): 18.5–24.9 and aged between 19 and 30) from Auburn University, AL. All subjects recruited were free of any documented musculoskeletal injuries or cardiovascular diseases. Subject demographic data (age, height, weight and BMI) were collected (Table 5.1). This study was approved by the Auburn University Institutional Review Board (IRB) (Appendix III).

Table 5.1. Subject Demographics.

| | Age (years) | | Height (cm) | | Weight (kg) | | BMI | |
|---|---|---|---|---|---|---|---|---|
| | Male | Female | Male | Female | Male | Female | Male | Female |
| Mean | 25.67 | 24.5 | 177.75 | 164.33 | 76.5 | 56.25 | 24.21 | 20.81 |
| SD | 2.02 | 1.73 | 2.96 | 2.53 | 3.12 | 3.91 | 0.6 | 1.03 |

### 5.3.3 Postures

Five different locomotive postures were used by subjects to travel up to 300 feet (91.4m) in this study: Upright Walking (UW), Stoop-Walking (SW), Knee and Hand Crawling (KHC), Foot and Hand Crawling (FHC), and Low Crawling (LC) in a randomized order.

### 5.3.4 Equipment

A 300-foot (91.4m) slightly curved concrete test track was established with safety cones and barriers, on the third floor of the Auburn University Coliseum. The test track was marked every thirty (30) feet (9.14m). The start and finish lines were set 10 feet (3.05m) from the beginning and the end of the track, respectively, to control any acceleration or deceleration effect.

Xsens 3D motion capture system was used to track subject movements. Seventeen (17) matchbook-sized (45mm x 30mm x 11mm) motion trackers were strapped around various body segments (head, sternum, left shoulder, right shoulder, left upper arm, right upper arm, left fore-arm, right fore-arm, left hand, right hand, pelvis, left upper leg, right upper leg, left lower leg, right lower leg, left foot and right foot). Subject kinematic data were recorded and used to construct a linked segment model consisting of the head, trunk, upper arm, forearm, hand, thigh, leg and foot. This model was used to calculate parameters including stride duration, stride length, interlimb coordination patterns, and points of contact to the ground. Xsens's MVN Studio software was used for analyzing all motion data.

A Heart Rate Monitor (Garmin Forerunner 110) was used to measure continuous heart rate. Knee pads, elbow pads, and gloves were provided to subjects while performing the crawling activities.

### 5.3.5 Procedure

Subjects participated in a pre-trial session which provided a chance to familiarize them with the five different locomotive postures used in the study. They were instructed to be well rested in the previous 12 hours, well hydrated, and caffeine free for at least 3 hours prior to the experiment. After subjects provided informed consent (Appendix III), each subject's age, gender, and anthropometric data (height, weight, arm span, foot length, etc.) were recorded. Subjects were instrumented with a Garmin heart rate monitor to record resting and locomotive heart rates. In addition, Xsens sensors were strapped around various body segments (head, sternum, left shoulder, right shoulder, left upper arm, right upper arm, left fore-arm, right fore-arm, left hand, right hand, pelvis, left upper leg, right upper leg, left lower leg, right lower leg, left foot and right foot) to record subject kinematic data. Subjects were instructed to use the five different locomotive postures: UW, SW, KHC, FHC and LC in a randomized order to travel up to 300 feet (91.4 m) swiftly in different trials. An investigator closely followed each subject, while pushing a cart with a digital video camera mounted to record the entire of each trial. Subjects were provided sufficient rest periods to ensure their resting heart rate return to within 10% of their initial resting heart rate, between successive trials. All subjects were required to wear knee/elbow pads and gloves while performing the crawling activities. 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 predicted HR max (220-age); or stop requested by subject.

### 5.3.6 Project Analysis

Independent variables in this study were the five different locomotive postures and gender. Dependent variables were kinematic data including step cycle time (s/cycle), stride length (ft), interlimb coordination patterns, and points of contact to the ground. Videos of linked segment models were analyzed frame by frame to detect the locomotion of four limbs, interlimb coordination patterns, and points of contact to the ground during walking and crawling. Kinematic data were analyzed using analysis of variance (ANOVA). Post hoc tests were performed using Tukey’s Honestly Significant Difference (HSD) test. Type I error rates were set at 0.05 for all statistical tests.

## 5.4 Results

Subject kinematic data were recorded by the Xsens 3D motion capture system. The frequencies of all Xsens 3D motion capture videos were set at 60 Hz for the entire study. Linked segment models were constructed for the five different locomotive postures: (1) UW, (2) SW, (3) FHC, (4) KHC, and (5) LC (Figure 5.1).

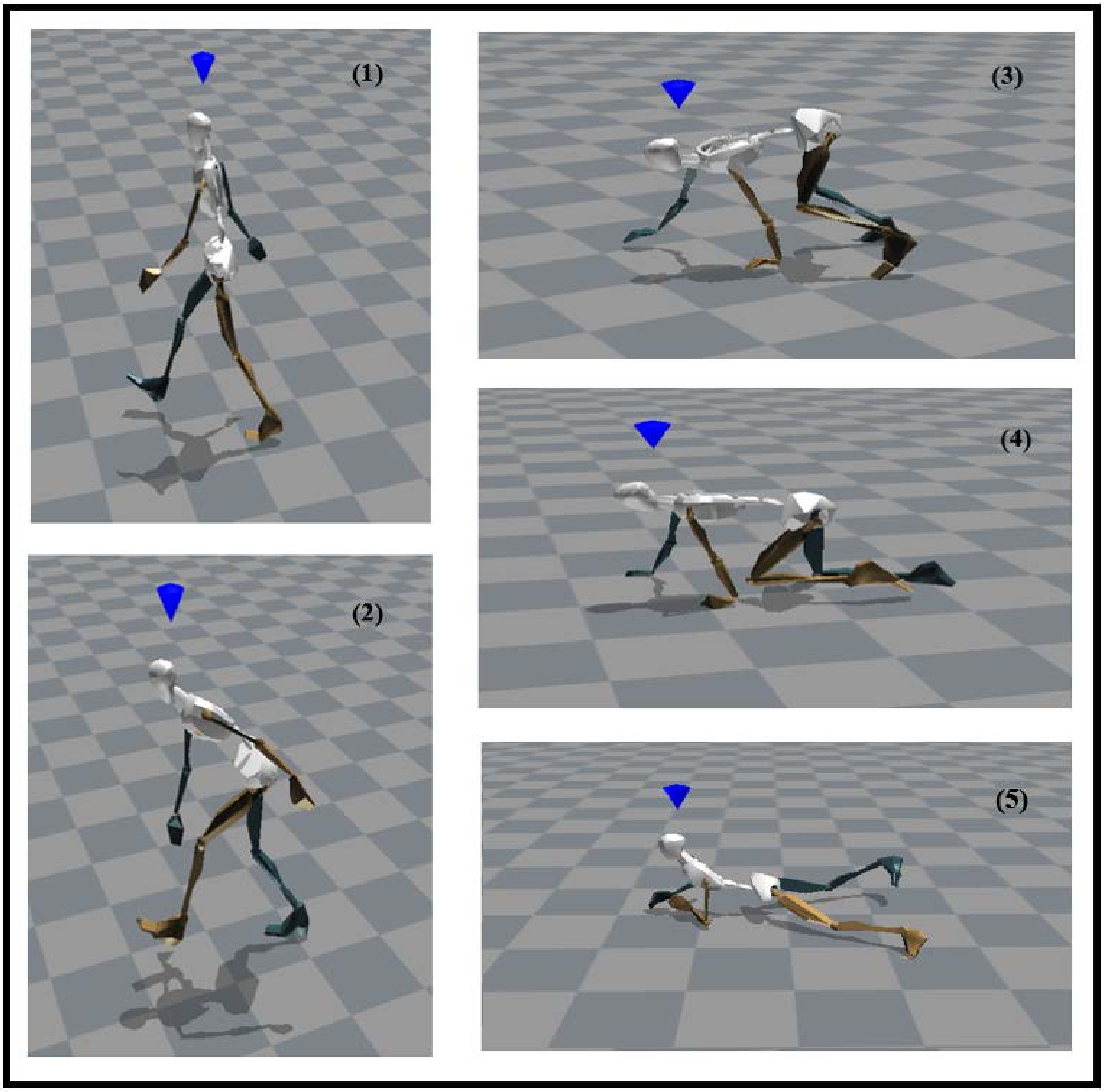


Figure 5.1. Linked Segment Models for Five Different Postures.

Videos of linked segment models were analyzed frame by frame to detect the locomotion of the four limbs (stance and swing) during walking and crawling (Figure 5.2). Parameters including step cycle time (s/cycle), stride length (ft), interlimb coordination patterns, and points of contact to the ground were calculated.

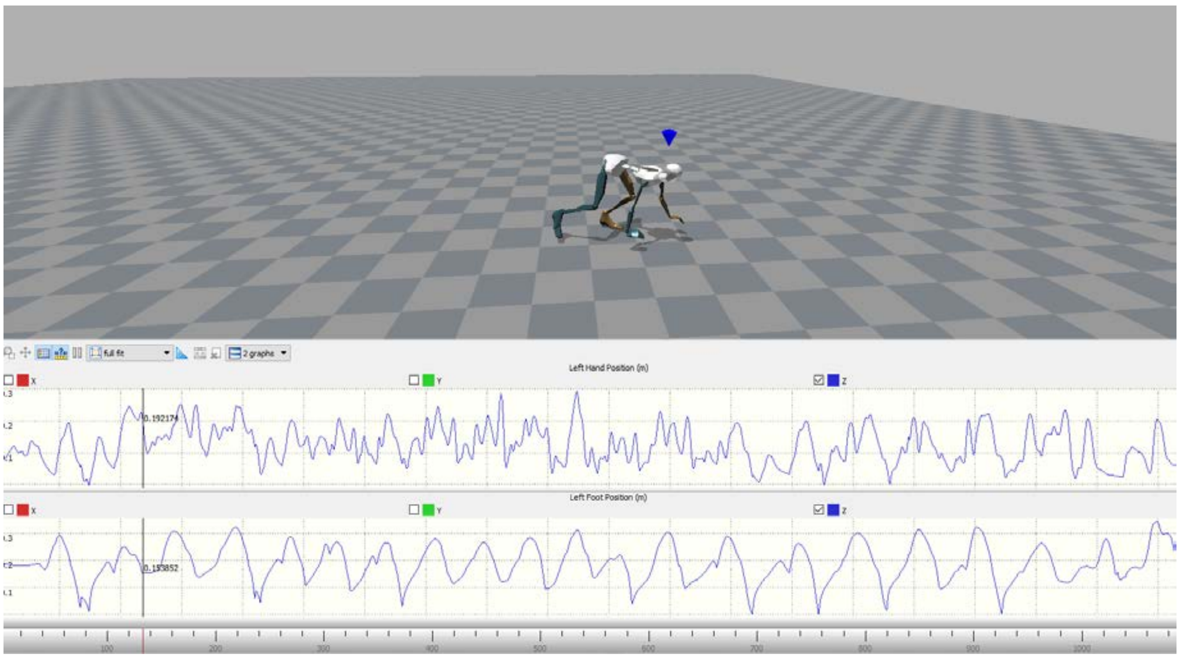


Figure 5.2. Xsens 3D Motion Capture Videos Frame by Frame.

Xsens provides an estimate of the position of each subject's body segments relative to a global coordinate frame defined during calibration. The time-series waveforms of arm segment and leg segment position were used to estimate crawling stride length and step cycle time (Figure 5.2). Specifically, each subject's step cycle time was defined as the duration between two consecutive valleys in the z-axis position signal of the left leg body segment. Points of contact to the ground were determined by counting the number of valleys present during a consecutive time frame of 20 samples for the different body segments that were expected to make contact with the ground (i.e., left leg, right leg, left arm, and right arm). For example, if a subject contacted the ground with his/her left leg and right leg in a consecutive 20 sample time frame for a certain crawling cycle, two valleys in the z-axis position signal would be counted to define the points of contact for that cycle.

Walking and crawling step cycle time (s/cycle) in this study was defined as the duration between two consecutive initiation stances of the left leg. Significant difference in step cycle time was detected among different postures in this study ($F_{4,88}$=174.19, p<0.001). Average UW and SW step cycle times were measured at 0.68 ± 0.09 s/cycle and 0.68 ± 0.08 s/cycle respectively. Average step cycle times for FHC, KHC and LC were measured at 1.01 ± 0.19 s/cycle, 0.69 ± 0.12 s/cycle, and 1.11 ± 0.10 s/cycle respectively. A post hoc Tukey HSD test showed that KHC had a shorter crawling cycle than FHC (p<0.05) and LC (p<0.05). Gender did not show any significant effect on step cycle time for any of the five locomotive postures (p>0.05). However, gender significantly affected stride length (p<0.001). Males had a longer stride than females in UW (p<0.001), SW (p<0.001), FHC (p<0.001) and LC (p=0.023) (Figure 5.3). Stride length for walking and crawling in this study was measured as the distance between two consecutive initiation stances of the left leg. Stride lengths were significantly different among the locomotive postures ($F_{4,88}$=160.32, p<0.001). Stride lengths in the walking trials were significantly longer than stride lengths in the crawling trials. Average UW and SW stride lengths were measured at 4.23 ± 1.02 ft (1.29 ± 0.31 m) and 4.02 ± 0.82 ft (1.23 ± 0.25 m). Stride length in FHC was longer than stride length in KHC (p<0.05) and stride length in LC (p<0.05). Average stride lengths in FHC, KHC and LC were measured at 3.77 ± 0.98 ft (1.15 ± 0.30 m), 1.92 ± 0.10 ft (0.59 ± 0.03 m) and 2.78 ± 0.30 ft (0.85 ± 0.09 m) respectively.

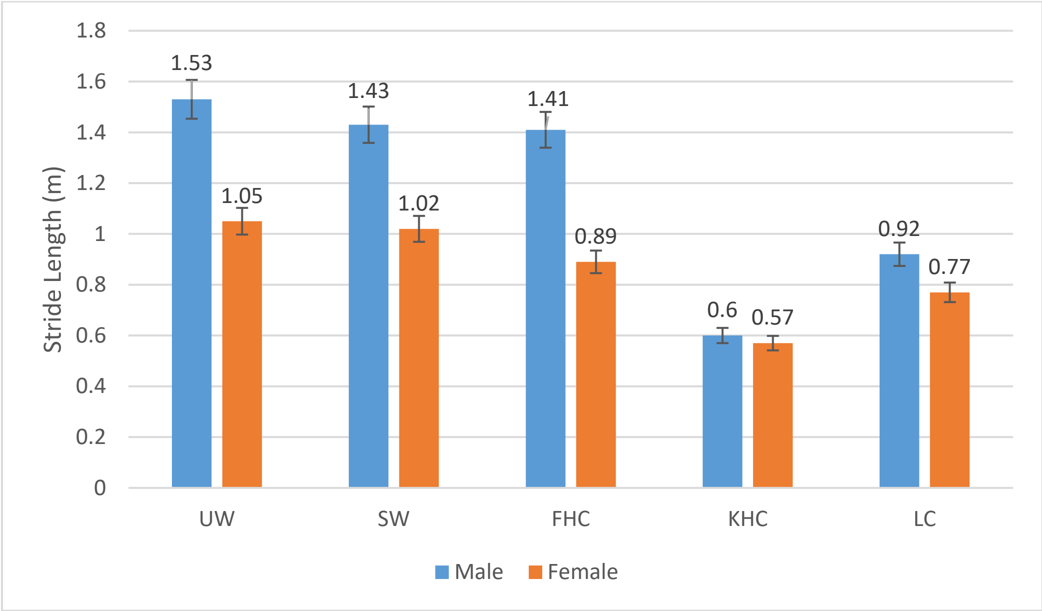


Figure 5.3. Stride Lengths for Different Locomotive Postures.

Stride lengths measured in this study were normalized with subjects' stature (m). Results indicated that normalized stride length in FHC was longer than normalized stride length in KHC ($p<0.05$) and normalized stride length in LC ($p<0.05$). Males had a longer normalized stride than females in UW ($p<0.001$), SW ($p<0.001$), FHC ($p<0.001$) and LC ($p<0.001$).

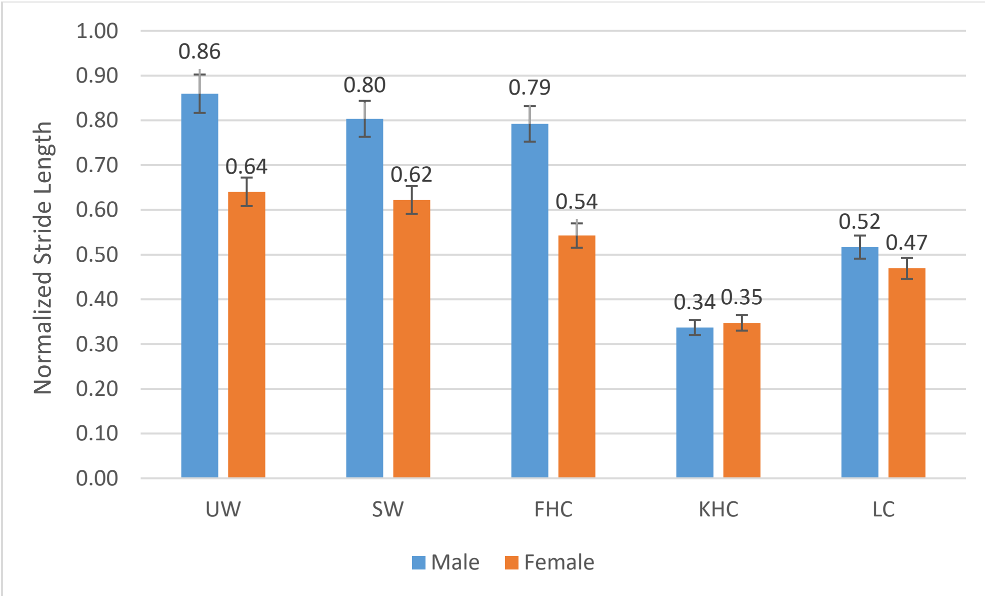


Figure 5.4. Normalized Stride Lengths for Different Locomotive Postures.

Interlimb coordination patterns among the four limbs during walking and crawling were detected. Interlimb coordination was defined as the relative timing of the four limbs movement (stance and swing) by analyzing Ipsilateral Phase Lag (IPL), which is the phase lag between the stance of the left arm and the stance of the left leg. In this study, IPL value between 40% and 60% was a “trot-like” gait, which indicated that diagonal limbs entered stance together. IPL value between 0% and 10% or between 90% and 100% was a “pace-like” gait, which indicated that ipsilateral limbs entered stance at the same time. IPL value between 11% and 39% or between 61% and 89% indicated no pairing of limbs. Interestingly, in this study, subjects’ interlimb coordination patterns were more constant during the first 50 feet (15.2 m) of crawling of all three crawling trials. In FHC, 9 out of 24 subjects showed a “trot-like” gait with IPL close to 50%, 3 subjects showed a “pace-like” gait and 6 subjects did not exhibit any pairing of limbs. In KHC, more than half (15 out of 24) subjects showed a “trot-like” gait. In the LC trial, most subjects exhibited a “trot-like” gait or no pairing of limbs (Table 5.2). However, after 50 feet (15.2 m), limb coordination for subjects began to become inconsistent. Subjects were more likely to use combined gaits ("Trot-like", "Pace-like" and "No pairing") during crawling. In this study, gender effect on interlimb coordination patterns was not detected.

Table 5.2. Limb Coordination Patterns for Different Crawling Postures before 50 Feet (15.2 m).

| | FHC | KHC | LC |
|---|---|---|---|
| "Trot-like" Gait (IPL: 40%~60%) | 9/24 | 15/24 | 7/24 |
| "Pace-like" Gait (IPL: 0%~10% or 90%~100%) | 3/24 | 1/24 | 3/24 |
| No Pairing of Limbs (IPL: 11%~39% or 61%~89%) | 6/24 | 7/24 | 9/24 |
| Combination of Different Gaits (IPL varied) | 6/24 | 1/24 | 5/24 |

Subjects maintained a two-point contact (diagonal limbs) to the ground for most of the time during the first 50 feet (15.24 m) of KHC, FHC and LC trials. Three-point contact or four-point contact to the ground were observed after crawling 50 feet (15.24 m). However, no difference in points of contact to the ground was found among different crawling postures.

### 5.5 Discussion

The purpose of this study was to perform a kinematic analysis of different locomotive postures. Average stride lengths measured in the walking trials were significantly longer than stride lengths in the crawling trials. Short stride lengths in crawling activities could be a result of decreased lower-limb lever arm in crawling postures (hip to knee as opposed to hip to foot) [Chaffin, Andersson, and Martin, 2006]. Average stride length in FHC was measured at 3.77 ±

0.98 ft (1.15 ± 0.30 m), which was significantly longer than stride length in KHC (1.92 ± 0.10 ft (0.59 ± 0.03 m)) and stride length in LC (2.78 ± 0.30 ft (0.85 ± 0.09 m)). Those findings are similar to crawling velocities reported in chapter 3 of this dissertation. In chapter 3, travel velocities in walking trials were approximately twice as fast as velocities in crawling trials. Average FHC speed was measured at 3.93 ± 0.95 ft/s (1.20 ± 0.29 m/s), which was significantly faster than KHC and LC. The increased travel velocity achieved in walking trials and FHC could be a function of increased stride length compared to KHC and LC. Results also indicated that males had a longer stride than females in UW, SW, FHC and LC. This may be due in part to the stature difference between males and females.

Interlimb coordination patterns and points of contact to the ground were also detected for different crawling postures in this study. Results indicated that subjects' interlimb coordination patterns were much more constant during the first 50 feet (15.24 m) of crawling. Most subjects maintained a "trot-like" gait (diagonal limbs enter stance together) and two-point contact (diagonal limbs) to the ground during first 50 feet (15.24 m) of crawling, while three-point contact or four-point contact to the ground were observed after 50 feet (15.24 m) of crawling. One reasonable explanation for the alternation of interlimb coordination and points of contact to the ground is the change of crawling speed. In chapter 3 of this dissertation, results indicated that crawling speed decreased significantly after the first thirty (30) feet (9.14 m) of travel. A previous study also reported that crawling speed caused transitions between interlimb coordination patterns [Patrick et al., 2009]. Patrick et al. [2009] demonstrated that at a slow (0.72 ft/s (0.22 m/s)) crawling velocity, interlimb coordination tended to be like "no pairing", while at a high (4.40 ft/s (1.34 m/s)) crawling velocity, coordination became more "trot-like" or "pace-like". Another study by Babic et al. [2001] claimed that as speed increased, crawling tended to change from three or four-point stance phases to two-point stance phases (one hand and contralateral knee were on the ground).

Results of this study such as step cycle time, stride length and interlimb coordination can provide insight regarding kinematics of different locomotive postures and provide recommendations for crawling effectiveness during evacuation. Additionally, studying the crawling activity in evacuation conditions may also be helpful to train emergency responders (e.g., firefighters) so that they can be more effective when performing rescue activities under the Immediately Dangerous to Life and Health (IDLH) conditions.

The limitations of this study include: 1) velocity was not controlled in this study. Subjects performed walking and crawling trials at their own paces, which may affect the interlimb coordination pattern or points of contact to the ground in this study; 2) this study was performed on a slightly curved concrete test track, which may have some effects on subject’s interlimb coordination.

### 5.6 Conclusions

The following conclusions are drawn from the current study:

1) KHC has a shorter crawling cycle than FHC and LC. There is no significant difference in step cycles between UW and SW.
2) Males have a longer stride than females in UW, SW, FHC and LC.
3) Interlimb coordination patterns are more consistent during the first 50 feet (15.24 m) of crawling. Subjects tend to maintain a “trot-like” gait during the first 50 feet (15.24 m) of crawling. After 50 feet (15.24 m), combined gaits are used by subjects.

4) Subjects tend to maintain two-point contact (diagonal limbs) to the ground for the most of time during the first 50 feet (15.24 m) of crawling. After 50 feet (15.24 m), three-point contact or four-point contact to the ground is maintained by subjects.
5) Gender has no effect on interlimb coordination pattern or points of contact to the ground during crawling.

Chapter 6

# Conclusions

## 6.1 Summary of Findings

This research focused on the effect of posture on evacuation performance and physiological demands. A review of the literature indicated that atypical postural locomotion has not been fully studied and most available crawling research has not been conducted in an evacuation context. Lack of relevant research poses difficulties in answering the questions: “Can people successfully evacuate?” and “How fast can people evacuate?” under current standards for emergency evacuation route and exit design. Current International Building Code (IBC) [2015] standards enforce that the distance to an exit should not exceed 250 feet. However, there is no clear evidence that humans can crawl that distance. This research investigated five different postures (Upright Walking (UW), Stoop-Walking (SW), Foot and Hand Crawling (FHC), Knee and Hand Crawling (KHC), and Low Crawling (LC)) corresponding to five different breathing zone heights on a 300-foot (91.4 m) test track to determine whether locomotive posture affected travel speed, travel distance and physiological workload. This study also reported kinematic data for different locomotive postures, including stride duration, stride length, interlimb coordination patterns, and points of contact to the ground. The results of the research can be summarized as follows:

1) Locomotive posture impacts human velocity and physiological demands. Crawling is significantly slower and more physically demanding (higher Average Heart Rate (HRavg) levels, higher Volumes of Oxygen consumption ($VO_2$), higher Ventilation Rates ($V_E$), and higher Respiratory Exchange Ratios (RER)) than walking. Further, Foot and Hand Crawling (FHC) is faster, but perceived to be much more physically demanding than both Knee and Hand Crawling (KHC) and Low Crawling (LC).
2) Crawling velocities decrease significantly as travel distance increases. Average maximum crawling distance is less than 250 feet (76.2 m).
3) Crawling is an intense activity (RER>1.0) that requires more recovery time compared to walking.
4) 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. But gender has no significant effect on Heart Rate (HR) levels, Volumes of Oxygen consumption ($VO_2$), Ventilation Rates ($V_E$), and Respiratory Exchange Ratios (RER) during crawling.
5) Knee Hand Crawling (KHC) has a shorter crawling cycle than Foot and Hand Crawling (FHC) and Low Crawling (LC). There is no significant difference in step cycle between Upright Walking (UW) and Stoop-Walking (SW).
6) Males have a longer stride than females in Upright Walking (UW), Stoop-Walking (SW), Foot and Hand Crawling (FHC) and Low Crawling (LC). But gender has no effect on interlimb coordination pattern or points of contact to the ground during crawling.

7) Interlimb coordination patterns are much more consistent during the first 50 feet (15.24 m) of crawling. Subjects tend to maintain a "trot-like" gait during the first 50 feet (15.24 m) of crawling. After 50 feet (15.24 m), combined gaits are used by subjects.
8) Subjects tend to maintain two-point contact (diagonal limbs) to the ground for the most of time during the first 50 feet (15.24 m) of crawling. After 50 feet (15.24 m), three-point contact or four-point contact is maintained by subjects.

Results of the study can provide a way to evaluate human capabilities and limitations during evacuation and give additional guidance about the effects of different postures (breathing zone heights) on egress performance, which supports the design of building evacuation routes. As expected, walking is significantly faster and less physically demanding than crawling. During fire emergency evacuations, being bipedal (e.g., walking, stoop-walking) is an optimal locomotive mean of evacuation. If bipedal locomotion is not available, quadrupedal locomotion (crawling) should be adopted. Different crawling postures should be adopted based on environment conditions (breathing zone heights, vision levels, obstacles, etc.). Certain crawling postures have advantages over others. Foot and Hand Crawling (FHC) is faster, but perceived to be much more physically demanding than both Knee and Hand Crawling (KHC) and Low Crawling (LC).

In the present study, average maximum crawling distance for Foot and Hand Crawling (FHC), Knee and Hand Crawling (KHC) and Low Crawling (LC) were measured at 150.21 ft (45.78 m), 182.92 ft (55.75 m) and 172.58 ft (52.60 m), respectively, which are much shorter than the current International Building Code (IBC) [2015] standards allowing a distance up to 250 feet (76.2 m) to an exit. Fast walking for 250 feet (76.2 m) may be achievable and not very demanding during evacuation, but it is extremely difficult for an evacuee to crawl 250 feet (76.2 m). This present study was conducted in optimal conditions and subjects were healthy college students (‘normal’ Body Mass Index (BMI): 18.5–24.9 and aged between 19 and 30). Crawling performance (velocity and maximum distance) during evacuation could be diminished even more in real fire conditions with aged and/or obese people. Therefore, current standards should take crawling evacuation into consideration and consider a shorter distance (less than 250 feet (76.2 m)) to access an exit for evacuation routes in future designs.

## 6.2 Limitations of Study

The limitations of the study can be categorized as follows:

1) Participant representation: this research was based on a limited sample. 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. Evacuation performance (locomotive velocity and travel distance) and physiological demand could be negatively impacted if different age groups or higher BMI subjects were tested.
2) Experimental condition settings: this study was conducted in a controlled environment (normal, room-temperature, smooth, dry, and flat surface conditions). As in real evacuation scenarios, confounding variables may have an impact on the results. For example, decrease in performance could be greater if this study was performed under conditions with obstacles, thermal stress and limited visibility.
3) Experimental devices: in the present study, subjects were instrumented with a COSMED K4b2 unit (~ 5 pounds) and 17 Xsens matchbook-sized (45mm x 30mm x 11mm) motion trackers. They also wore a COSMED K4b2 face mask to record their respiratory responses.

The COSMED K4b2 unit and the motion trackers mounted on the body could somewhat affect movement. The use of a respiratory face mask could also negatively impact (discomfort, vision degradation, etc.) walking and crawling in the present study.

4) Stopping criteria: in the present study, crawling trials were immediately stopped if subjects reached their 85% age-predicted maximum heart rate. However, reaching 85% age-predicted maximum heart rate may not exactly represent reaching subjects' maximum crawling distance.

### 6.3 Recommendations for Future Research

Future research should be conducted with larger samples with a focus on different occupant characteristics such as age and BMI. Another factor that future study can consider is simulating the evacuation environment. For example, recruit subjects to evacuate (walk and crawl) from a hot and low visibility environment to simulate a building fire evacuation. In addition, research is also needed in crawling on different types of surfaces with obstacles present to detect the effect on evacuation performance. It is important to simulate real fire conditions as much as practical for the reason that most fire in buildings will create a deleterious environment and the deterioration of environmental conditions significantly affects evacuation performance.

References


Abitbol, M. (1988). "Effect of Posture and Locomotion on Energy Expenditure." *American Journal of Physical Anthropology*. Vol. 77, October 1988, pp. 191-199.

Akizuki, Y., Yamao, K., and Tanaka, T. (2007). "Experimental Study on Walking Speed in Escape Route Considering Luminous Condition, Smoke Density and Evacuee's Visual Acuity." *7th Asia-Oceania Symposium on Fire Science and Technology*, Hong Kong, 2007.

Amelsvoort, L., Schouten, E., Maan, A., Swenne, C., and Kok, F. (2000). "Occupational Determinants of Heart Rate Variability." *International Archives of Occupational and Environmental Health.* Vol. 73, May 2000, pp. 255-262.

American College of Sports Medicine (ACSM). (2007). *ACSM's Metabolic Calculations Handbook.* American College of Sports Medicine. 2007.

Armstrong, L., Brubaker, P., Whaley, M., and Otto, R. (2006). *ACSM's Guidelines for Exercise Testing and Prescription (7th ed.).* 2006.

Babic, J., Karcnik, T., and Bajd, T. (2001). "Stability Analysis of Four-point Walking." *Gait & Posture.* Vol. 14, July 2001, pp. 56-60.

Bajd, T., Zefran, M., and Kralji, A. (1995). "Timing and Kinematics of Quadrupedal Walking Pattern." *Proceedings of IEEE/RSJ, International Conference on Intelligent Robots Systems.* 1995, pp. 303-307.

Barnard, R., and Duncan, H. (1975). "Heart Rate and ECG Responses of Firefighters." *Journal of Occupational Medicine.* Vol. 17, April 1975, pp. 247-250.

Bendall, M., Bassey, E., and Pearson, M. (1989). "Factors Affecting Walking Speed of Elderly People." *Age and Ageing*. Vol. 18, 1989, pp. 327-332.

Bhattacharya, A., and McGlothlin, J. (2012). *Occupational Ergonomics: Theory and Applications.* CRC Press, March 2012, ISBN-10: 1439819343.

Bohannon, R. (1997). "Comfortable and Maximum Walking Speed of Adults Aged 20-79 Years: Reference Values and Determinants." *Age and Ageing.* Vol. 26, 1997, pp. 15-19.

Bohannon, R., Andrews, A., and Thomas, M. (1996). "Walking Speed: Reference Values and Correlates for Older Adults." *Journal of Orthopaedic & Sports Physical Therapy*. Vol. 24, 1996, pp. 86-90.

Bouchard, D., and Trudeau, F. (2008). "Estimation of Energy Expenditure in a Work Environment: Comparison of Accelerometry and Oxygen Consumption/Heart Rate Regression." *Ergonomics.* Vol. 51, 2008, pp. 663-670.

Borg, G. (1998). *Borg's Perceived Exertion and Pain Scales.* Human Kinetics, 1998, ISBN: 0-88011-623-4.

Browning, R., Baker, E., Herron, J., and Kram, R. (2006). "Effects of Obesity and Sex on the Energetic Costs and Preferred Speed of Walking." *Journal of Applied Physiology*. Vol. 100, 2006, pp. 390-398.

Chaffin, D., Andersson, G., and Martin, B. (2006). *Occupational Biomechanics. 4th Edition.* Wiley, 2006, ISBN-10: 0471723436.

Cott, H., and Kinkade, R. (1972). *Human Engineering Guide to Equipment Design, Revised. ed.* McGraw Hill, 1972.

Dal, U., Erdogan, T., Resitoglu, B., and Beydagi, H. (2010). "Determination of Preferred Walking Speed on Treadmill may Lead to High Oxygen Cost on Treadmill Walking." *Gait & Posture*. Vol. 31, 2010, pp. 366-369.

Davis, J., and Gallagher, S. (2014). "Physiological Demand on Firefighters Crawling during a Search Exercise." *International Journal of Industrial Ergonomics.* Vol. 44, 2014, pp. 821-826.

Davis, J., Tang, R., and Sesek, R. (2014). "Evaluating Firefighter Crawling Performance in a Controlled Environment." *Advances in Safety Management and Human Factors.* 2014, pp. 3-9.

Davis, R. (2011). *A Comparison of Physiological Effects of Traditional Walking Locomotion to Crawling.* Thesis, East Stroudsburg University of Pennsylvania. 2011.

Dill, D. (1965). "Oxygen Used in Horizontal and Grade Walking and Running on the Treadmill." *Journal of Applied Physiology*. Vol. 20, 1965, pp. 19-22.

Dwyer, G., and Davis, S. (2005). *ACSM's Health-Related Physical Fitness Assessment Manual*. Lippincott, Williams & Wilkins, 2005. ISBN-10: 1451115687.

Flynn, T., Connery, S., Smutok, M., Zeballos, R., and Weisman, I. (1994). "Comparison of Cardiopulmonary Responses to Forward and Backward Walking and Running." *Medicine and Science in Sports and Exercise.* Vol. 26, 1994, pp. 89-94.

Francis, K., and Hoobler, T. (1986). "Changes in Oxygen Consumption Associated with Treadmill Walking and Running with Light Hand-carried Weights." *Ergonomics.* Vol. 29, 1986, pp. 999-1004.

Franzese, O., and Han, D. (2001). "A Methodology for the Assessment of Traffic Management Strategies for Large-scale Emergency Evacuations." *ITS America 11th Annual Meeting and Exposition*. Miami, Florida, 2001.

Freivalds, A., and Niebel, B. (2012). *Methods, Standards & Work Design (12th Edition)*, McGraw Hill, 2012, ISBN-10: 0073376310

Fudge, B., Wilson, J., Easton, C., Irwin, L., Clark, J., Haddow, O., Kayser, B., and Pitsiladis, Y. (2007). "Estimation of Oxygen Uptake during Fast Running Using Accelerometry and Heart rate." *Medicine and Science in Sports and Exercise.* Vol. 39, 2007, pp. 192-198.

Gallagher, S., Pollard, J., and Porter, W. (2011). "Locomotion in Restricted Space: Kinematic and Electromyographic Analysis of Stooped-walking and Crawling." *Gait & Posture*. Vol. 33, 2011, pp. 71-76.

Gamelin, F., Berthoin, S., and Bosquet, L. (2006). "Validity of the Polar S810 Heart Rate Monitor to Measure R-R Intervals at Rest." *Medicine and Science in Sports Exercise.* Vol. 38, 2006, pp. 887-893.

Getchell, N., Forrester, L., and Whitall, J. (2001). "Individual Differences and Similarities in the Stability, Timing Consistency, and Natural Frequency of Rhythmic Coordinated Actions." *Research Quarterly for Exercise and Sport.* Vol. 72, 2001, pp. 13-21.

Gulati, M., Shaw, L., Thisted, R., Black, H., Bairey, M., and Arnsdorf, M. (2010). "Heart Rate Response to Exercise Stress Testing in Asymptomatic Women: The st. James Women Take Heart Project." *Circulation.* Vol. 122, 2010, pp. 130-137.

Guyton, A., and Hall, J. (2005). *Textbook of Medical Physiology (11th ed.).* Saunders, 2005, ISBN-10: 0721602401.

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

Jin, T., and Yamada, T. (1989). “Experimental Study of Human Behavior in Smoke Filled Corridors.” *Proceeding of the 2$^{nd}$ International Fire Safety Science Symposium.* 1989, pp. 511-519.

Jones, B., Toner, M., Daniels, W., and Knapik, J. (1984). “The Energy Cost and Heart-rate Response of Trained and Untrained Subjects Walking and Running in Shoes and Boots.” *Ergonomics.* Vol. 27, 1984, pp. 895-902.

Kady, R., and Davis, J. (2009a). “The Effect of Occupant Characteristics on Crawling Speed in Evacuation.” *Fire Safety Journal.* Vol. 44, 2009, pp. 451-457.

Kady, R., and Davis, J. (2009b). “The Impact of Exit Route Designs on Evacuation Time for Crawling Occupants.” *Journal of Fire Sciences*. Vol. 27, 2009, pp. 481-493.

Knoblauch, R., Pietrucha, M., and Nitzburg, M. (1996). “Field Studies of Pedestrian Walking Speed and Start-up Time.” *Journal of the Transportation Research Board*. Vol. 1538, 1996.

Laukkanen, R., and Virtanen, P. (1998). “Heart Rate Monitors: State of the Art.” *Journal of Sports Sciences*. Vol. 16, 1998, Suppl: S3-7.

MacLellan, M., Ivanenko, Y., Cappellini, G., Sylos, A., Labini, F., and Lacquaniti, F. (2012). “Features of Hand-foot Crawling Behavior in Human Adults.” *Journal of Neurophysiology*. Vol. 107, 2012, pp. 114-125.

Malchaire, J., Wallemacq, M., Rogowsky, M., and Vanderputten, M. (1984). “Validity of Oxygen Consumption Measurement at the Workplace: What Are We Measuring?” *Annals of Occupational Hygiene.* Vol. 28, 1984, pp. 189-193.

Martin, P., Rothstein, D., and Larish, D. (1992). “Effects of Age and Physical Activity Status on the Speed-aerobic Demand Relationship of Walking.” *Journal of Applied Physiology*. Vol. 73, 1992, pp. 200-206.

Mattsson, E., Larsson, U., and Rössner, S. (1997). “Is Walking for Exercise too Exhausting for Obese Women?” *International Journal of Obesity and Related Metabolic Disorders*. Vol 21, 1997, pp. 380-386.

Merriam-Webster. (2014). *The Merriam-Webster Dictionary.* Merriam-Webster Mass Market, 2004, ISBN-10: 087779930X.

Morrissey, S., George, C., and Ayoub, M. (1985). "Metabolic Costs of Stoopwalking and Crawling." *Applied Ergonomics.* Vol.16, 1985, pp. 99-102.

Moss, K. (1934). "The Energy Output of Coal Miners during Work." *Transactions of the American Institute of Mining and Metallurgical Engineers.* Vol. 189, 1934, pp.132-49.

Muhdi, R., Davis, J., and Blackburn, T. (2006). "Improving Occupant Characteristics in Performance-based Evacuation Modeling." *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*. Vol. 50, 2006, pp. 1199-1203.

Murray, M., Spurr G., Sepic S., Gardner G., and Mollinger L. (1985). "Treadmill vs. Floor Walking: Kinematics, Electromyogram, and Heart Rate." *Journal of Applied Physiology*. Vol. 59, 1985, pp. 87-91.

Murry, M., Kory, R., Clarkson, B., and Speic, S. (1966). "Comparison of Free and Fast Speed Walking Patterns of Normal Men." *American Journal of Physical Medicine.* Vol. 45, 1966, pp. 8-23.

Nagai, R., Fukamachi, M., and Nagatani, T. (2006). "Evacuation of Crawlers and Walkers from Corridor through an Exit." *Physica A: Statistical Mechanics and its Applications*. Vol. 367, 2006, pp. 449-460.

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

National Institute for Occupational Safety & Health (NIOSH). (2013). "Fire Fighter Fatality Investigation and Prevention Program." *National Institute for Occupational Safety & Health (NIOSH)*. Retrieved from http://www.cdc.gov/niosh/fire/mapdata.html.

Occupational Safety and Health Administration (OSHA). (2015a). *OSHA General Industry CFR 1910.134 Subpart I - Personal Protective Equipment.* The U.S. Department of Labor, 2015, ISBN-10: 1599596059.

Occupational Safety and Health Administration (OSHA). (2015b). *OSHA General Industry CFR 1910.38 Subpart E - Means of Egress.* The U.S. Department of Labor, 2015, ISBN-10: 1599596059.

Occupational Safety and Health Administration (OSHA). (2015c). *OSHA General Industry CFR 1910.36 Subpart E - Means of Egress.* The U.S. Department of Labor, 2015, ISBN-10: 1599596059.

Occupational Safety and Health Administration (OSHA). (2015d). “OSHA Lead in Construction Advisor.” Retrieved from https://webapps.dol.gov/elaws/oshalead.htm.

Occupational Safety and Health Administration (OSHA). (2017) “Occupational Safety and Health Administration (OSHA) Evacuation Plans and Procedures eTool.” *The U.S. Department of Labor*. Retrieved from https://www.osha.gov/SLTC/etools/evacuation/.

Patrick, S., Noah, J., and Yang, J. (2009). “Interlimb Coordination in Human Crawling Reveals Similarities in Development and Neural Control with Quadrupeds.” *Journal of Neurophysiology*. Vol. 101, 2009, pp. 603-613.

Patton J. (1997). *Emerging Technologies for Nutrition Research: Potential for Assessing Military Performance Capability.* National Academies Press (US), 1997, ISBN-10: 0-309-05797-3.

Plowman, S., and Smith, D. (2013). *Exercise Physiology for Health, Fitness, and Performance.* LWW, 2013, ISBN-10: 1451176112.

Pollock, M., Miller, H., Janeway, R., Linnerud, A., Robertson, B., and Valentino, R. (1971). “Effects of Walking on Body Composition and Cardiovascular Function of Middle-aged Man.” *Journal of Applied Physiology*. Vol. 30, 1971, pp. 126-130.

Robergs, R., and Landwehr, R. (2002). “The Surprising History of the "HRmax=220-age" Equation.” *Journal of Exercise Physiology*. Vol. 5, 2002, pp. 1-10.

Sander, E., Alexander, T., and Peter, J. (2011). “Human Locomotion through a Multiple Obstacle Environment: Strategy Changes as a Result of Visual Field Limitation.” *Experimental Brain Research.* Vol. 212, 2011, pp. 449-456.

Simonson, D., and DeFronzo, R. (1990). “Indirect Calorimetry: Methodological and Interpretative Problems.” *The American Journal of Physiology.* Vol. 258, 1990, pp. 399-412.

Sothmann, M., Saupe, K., Jasenof, D., Blaney, J., Fuhrman, S., Woulfe, T., Raven, P., Pawelczyk, J., Dotson, C., Landy, F., Smith, J., and Davis, O. (1990). “Advancing Age and the Cardiorespiratory Stress of Fire Suppression: Determining a Minimum Standard for Aerobic Fitness.” *Human Performance.* Vol. 3, 1990, pp. 217-236.

Sparrow, W. (1989). “Creeping Patterns of Human Adults and Infants.” *American Journal of Physical Anthropology*. Vol. 78, 1989, pp. 387-401.

Sparrow, W., and Newell, K. (1994). “The Coordination and Control of Human Creeping with Increases in Speed.” *Behavioral Brain Research*. Vol. 63, 1994, pp. 151-158.

Tanaka, H., Monahan, K., and Seals, D. (2001). "Age-predicted Maximal Heart Rate Revisited." *Journal of American College of Cardiology*. Vol. 37, 2001, pp. 153-156.

Thomas, S., Reading, J., and Shephard, R. (1992). "Revision of the Physical Activity Readiness Questionnaire (PAR-Q)." *Canadian Journal of Sport Sciences*. Vol. 17, 1992, pp. 338-345.

Walt, W., and Wyndham, C. (1973). "An Equation for Prediction of Energy Expenditure of Walking and Running." *Journal of Applied Physiology*. Vol. 34, 1973, pp. 559-563.

Wannier, T., Bastiaanse, C., Colombo, G., and Dietz, V. (2001). "Arm to Leg Coordination in Humans during Walking, Creeping and Swimming Activities." *Experimental Brain Research*. Vol. 141, 2001, pp. 375-379.

Weippert, M., Kumar, M., Kreuzfeld, S., Arndt, D., Rieger, A., and Stoll, R. (2010). "Comparison of Three Mobile Devices for Measuring R–R Intervals and Heart Rate Variability: Polar S810i, Suunto t6 and an ambulatory ECG system." *European Journal of Applied Physiology*. Vol. 109, 2010, pp. 779-786.

Appendices

Appendix I

Physical Activity Readiness Questionnaire (PAR Q) [Thomas, Reading, and Shephard, 1992].

**Subject#____**

**Questionnaire: Physical Activity Readiness Questionnaire (PAR Q)**

**Age____ Gender____ Height____ Weight_____ BMI____**

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
2. Do you feel pain in your chest when you do physical activity?
3. In the past month, have you had chest pain when you were not doing physical activity?
4. Do you lose your balance because of dizziness or have you ever lost consciousness?
5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?
6. Is your doctor currently prescribing drugs (for example, water pills) for blood pressure or heart condition?
7. Do you know of any other reason why you should not do physical activity?
8. Did you have any caffeine drinks prior to participating in this study? If yes, please indicate how much you drank.

Appendix II

Rating of Perceived Exertion (RPE) Chart [Borg, 1998].

**Subject#____** **Posture_____**

**Rating of Perceived Exertion (RPE) chart**

Please refer the Rating of Perceived Exertion (RPE) Scale below and rate the crawling activity you just performed.

**RPE SCALE**

**0 nothing at all**
**0.5 very, very weak**
**1 very weak**
**2 weak**
**3 moderate**
**4 somewhat strong**
**5 strong**
**6**
**7 very strong**
**8**
**9**
**10 very, very strong**
**Maximal**

Please write your rating here: ________________

Appendix III

Informed Consent

The Auburn University Institutional Review Board has approved this Document for use from 02/05/2017 to 02/27/2018
Protocol # 16-059 EP 1602

AUBURN UNIVERSITY

SAMUEL GINN
COLLEGE OF ENGINEERING

**INFORMED CONSENT**
For a Research Study Entitled
"The Impact of Crawling Postures on Speed and Physiological Demand"

You are invited to participate in a research study to find the impact of crawling postures on speed and physiological demands in evacuation. The study is being conducted under the direction of Jerry Davis, Associate Professor in Auburn University Department of Industrial and Systems Engineering. You were selected as a possible participant because you satisfy our recruitment criteria: 1) 'normal' Body Mass Index (BMI) 18.5–24.9; 2) age from 19 to 30; 3) capability to perform moderate physical activity.

**What the study is about?**
In emergencies, humans may adopt postures other than walking during evacuation. National Fire Protection Association (NFPA) [2015] statistics indicate that most fire deaths are not caused by direct burns but by smoke inhalation. According to fire evacuation tips from the NFPA, evacuees are instructed to crawl low under smoke during severe fire evacuation [NFPA, 2015]. The purpose of this study is to detect effects of postures on evacuation velocities and physiological demands.

**What will be involved if you participate?**
You will participate in this study by traveling 300 feet (91.44m) using five different locomotive postures: normal walking, stooped walking (walking with the head and back bent forward), feet and hand crawling (crawling with feet and hands on the ground), knee and hand crawling (crawling with knees and hands on the ground), and low crawling (crawling with knees and forearms on the ground, and crawl by extending arms in front of chest, and pulling.). Your travel speed, as well as heart rate and respiratory responses will be recorded. A 3D motion tracking system-Xsens will be used to collect data including step cycle duration, stride length and arm and leg coordination patterns. This study evaluates human movement as a function of breathing zone height using different styles of locomotion. Results of the study can provide additional guidance about the effects of different postures on evacuation speed and energy costs during evacuation and have implications for future building layouts.
This study will take place on the 3rd floor of Shelby Center, Auburn University. You will perform five trials in this study and you need to use different crawling postures to crawl 300 foot in each trial. Your total time contribution will be around 2 hours.

<u>Experiment Procedure:</u>
1) Experiments will take place on the 3rd floor hallway of Shelby Center after 4:45 PM.
2) Your height and weight will be measured and recorded by the investigator.
3) You will be asked to fill out a questionnaire PAR-Q about your medical history to see if it is possible for you to perform this study.
4) You will participate in five trials during this study. You need to use different postures to travel

 Participant's initial________

300 foot in each trial. Five different postures in this study are: (1) Normal Walking (NW) (2) Stooped Walking (SW): walking with the head and back bent forward (3) Knee and Hand Crawling (KHC): crawling with knees and hands on the ground. (4) Foot and Hand Crawling (FHC): crawling with feet and hands on the ground. (5) Low crawling or army crawling (LC): crawling with knees and forearms on the ground, and crawl by extending arms in front of chest, and pulling. The order of each crawling posture trial will be randomly assigned to you.

5) You will wear knee pads, elbow pads, and gloves for each trial. After some warm-up exercise, you will attend a familiarization session to let you get familiar with the crawling postures used in the present trial. This session should last approximately 10 minutes.

6) You will put on a Heart rate monitor which is comprised of two elements: a chest strap transmitter and a wrist receiver to record your heart rate response.

7) 3D motion tracking system-Xsens markers will be placed on different body parts including your head, back and shoulders, upper arms, lower arms and legs.

8) You will also be instrumented with a COSMED K4b2 main unit and battery kit (~ 5 pounds in total) to record your respiratory response including oxygen consumption and carbon dioxide production.

9) You will be asked is there any discomfort about wearing heart rate monitor, X-sens markers and COSMED mask before continuing the study. If you feel discomfort in wearing those devices, the investigator will help to rearrange them.

10) You will be asked to sit in Room 3323, Shelby Center, to rest your heart rate for 5 minutes. Your resting heart rate and resting oxygen consumption will be recorded. Investigators will make sure video cameras are working and that video capture is not identifying participants.

11) During the crawling trials, you are allowed to stop and rest. You will be provided sufficient rest periods to ensure that your post-trial oxygen consumption returns to within 10% of your initial oxygen consumption, and your resting heart rate returns to within 10% of your initial resting heart rate, between successive trials. Knee/elbow pads and gloves will be provided while performing the crawling activities.

14) Stopping criteria [Dwyer and Davis., 2005] for the trials are: Onset of chest pain or chest pain-like symptoms; Signs of light-headedness, confusion, loss of full control of bodily movements, pale appearance, nausea, appearance of a blue or purple coloration of the skin or cold skin; Physical or verbal show of severe fatigue; Injury; Test equipment failure; 85% of subject age predicted HR max is reached (220-age); or the subject requests to stop.

15) You will be cooled down post exercise and retained until returning within 10% of your initial resting heart rate, subsequently thanked and released.

16) The whole experiment should take around 2 hours.

**Are there any risks or discomforts?**

This study asks you to crawl a 300 foot track. The risk of this study is similar to the risk of daily exercise. The main risks of this study are: 1) pulled muscles, 2) sprains and strains, 3) excessive loss of water from the body.

The other discomfort of our study is the potential invasion of privacy. Personal identifiable information about you (your face) may appear in the video recording.





Participant's initial________

The Auburn University Institutional Review Board has approved this Document for use from 02/05/2017 to 02/27/2018
Protocol # 16-059 EP 1602

**Are there any benefits to yourself or others?**

Research result may develop recommendations to improve evacuation performance and decrease physical demands when crawling during evacuation.

**Are there any costs?**

If you decide to participate, you will not incur any costs.

**If you change your mind about participating,** you can withdraw at any time during the study. Your participation is completely voluntary. If you choose to withdraw, your data and file can be withdrawn. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University, the Samuel Ginn College of Engineering, the Department of Industrial and Systems Engineering.

**Your privacy will be protected.** Any information obtained in connection with this study will remain confidential. Data files and videos will be grouped according to generic, unique subject labels (s1, s2, etc), which will not be linked in any way to your identity. Hard copy of consent forms, questionnaires and rating of perceived exertion (RPE) chart will be stored in a locked cabinet in Dr. Davis's office (Shelby Center Room 3310). Electronic data including test video records, heart rate data and EMG data will be stored in a password-protected computer in Dr. Davis's office (Shelby Center Room 3310). Only Dr. Davis and Li Cao will have access to those data files. Information obtained through your participation may be published in a professional journal and / or presented at a professional meeting. All data files will remain in PI's office for 3 years following the study, after which it will be destroyed. Consent forms, questionnaires and RPE chart will be shredded. Electronic data including videos will be deleted from computer.

If you have any questions about this study, please contact Li Cao by phone (979)-739-6513 or Email at lzc0023@auburn.edu or contact Dr. Jerry Davis by phone (334) 844-1424 or Email at davisga@auburn.edu. A copy of this document will be given to you to keep.

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone (334)-844-5966 or E-mail at hsubjec@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOU SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

| | | | |
|---|---|---|---|
| ____________________ | ______ | ____________________ | ______ |
| Participant's Signature | Date | Investigator Obtaining Consent Signature | Date |
| ____________________ | | ____________________ | |
| Printed Name | | Printed Name | |