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Evaluating the physical demands on firefighters using hand-carried stair descent devices to evacuate mobility-limited occupants from high-rise buildings

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ABSTRACT

The physical demands on firefighting personnel were investigated when using different types of hand-carried stair descent devices designed for the emergency evacuation of high rise buildings as a function of staircase width and evacuation urgency. Twelve firefighters used three hand-carried stair descent devices during simulated urgent and non-urgent evacuations. The devices were evaluated under three staircase width conditions (0.91, 1.12, and 1.32 m). For comparison, an urgent manual carry was also performed on the 1.12 m wide stairs. Dependent measures included electromyographic (EMG) data, heart rates, Borg Scale ratings, task durations and descent velocities. Results indicated that the *stair chair with extended front handles*, which allows the front person to descend the stairs facing forward, reduced the time integrated back muscle EMG by half and showed a descent velocity that was 1.8 times faster than the other stair descent devices in the study. There were no differences across staircase widths.

1. Introduction

Fire service personnel are often the first people called upon when evacuating large multi-story buildings during both emergency and non-emergency conditions, for example, extended power outages. During such evacuations, firefighters (FF) may need to transport building occupants with motor disabilities down several flights of stairs. Epidemiologic data from Emergency Medical Service (EMS) workers suggest that such tasks are often associated with injury development (Gershon et al., 1995; Hogya and Ellis, 1990; Karter and Molis, 2011; Maguire et al., 2005). Furber et al. (1997), in their study of 477 workers' compensation claims made by Australian ambulance workers, found that within private residences stairs were a strong factor contributing to injuries reported by ambulance officers. Our prior work, comparing simulated stair descents with a hand-carried stair chair, a backboard, and a stretcher, found that even with a lightweight mannequin (48 kg), a significant percentage of population would not have adequate back strength and would likely experience compression forces in excess of 3000 N (Lavender et al., 2000) when performing these evacuations tasks.

Stair transport tasks can be done by using one- or two-person manual carry techniques or, if available, by using one of several different types of stair descent devices. Hand-carried evacuation chairs are commonly used by fire department personnel and often found on emergency response vehicles. Alternatively, emergency stair descent devices may be owned by building occupants or building owners and used by fire service personnel during evacuations. While several stair descent devices or "evacuation chairs" are currently on the market for emergency evacuation of individuals with motor disabilities from high rise buildings, there is little empirical data indicating their impact on the physical demands placed on the firefighter who may be called upon to use these hand-carried chairs. The National Fire Protection Association (NFPA) Life Safety Code indicates that when descending stairs, an evacuation device should be easily operable by one person who is trained on its use, and that above average weight or strength should not be required for proper

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operation (NFPA 101-2009 Annex, A.7.2.12.2.3(2) (8)(a)). Moreover, subtle changes in equipment design can have substantial effects on the physical demands, especially when stair descent tasks include turns on landings (Lavender et al., 2007a,b; Fredericks et al., 2002). For example, Lavender et al. (2007a,b), found that changing handle locations on stair chairs significantly affected 90th percentile muscle recruitment levels as different chair handle configurations were carried through a landing. Fredericks et al. (2002) reported differences in spine compression estimated using the static strength prediction program across four types of hand-carried stair chairs. They found that designs that supported the lead person facing forwards when descending the stairs resulted in lower spine compression values for this lead individual.

Evacuation conditions including the staircase width and the urgency of the evacuation may also impact the physical demands on the firefighters, particularly if the stair descent involves landings where the direction of travel changes. Drury (1985) provided evidence that task performance measures, for example task duration or movement speed, are dependent upon the available space, at least up to the point where space no longer potentially restricts movement. Likewise, Karwowski and Alsabi (1991) reported a trend toward a lower acceptable weight of lift with more restricted lifting spaces. This implies that staircase dimensions could impact muscle recruitment levels as smaller versus larger landings are negotiated by evacuators. As for urgency, several studies have shown increases in biomechanical loading as movement speed increases (Marras, 2008). Under urgent evacuation conditions, one could expect more rapid motions, and perhaps more co-contraction of antagonistic muscles as the body is stabilized under the increased dynamic external loads.

The objective of this study was to compare biomechanical and physiological demands on firefighters as they used three existing hand-carried stair descent devices and a two-person manual carry without a chair.

Specifically, the following hypotheses were tested:

1. There are significant differences among existing hand-carried stair descent devices with regards to task performance measures and the physical demands placed on evacuators as measured via heart rate, electromyography, and subjective measures of perceived exertion.
2. The physical demands on the evacuator increase with narrower staircases.
3. The physical demands on the evacuator increase during urgent conditions.
4. The physical demands placed on the firefighters are dependent upon the combined effects of chair design, staircase width, and the level of evacuation urgency.

Additionally, the study assessed usability issues with each of the evaluated devices through video analysis and a structured interview process.

2. Methods

2.1. Participants

Twelve male professional firefighters between the ages of 20 and 46 (mean = 32 years) were recruited to serve as the evacuators for this study. Mean height and weight were 1.83 m (1.76–1.96 m) and 88 kg (71–118 Kg). Their fire service experience ranged from 1.5 to 17 years (mean = 6.6 years). All participants signed institutional review board approved consent documents.

2.2. Experimental design

A repeated measures randomized block experimental design was used in which participants experienced all combinations of the three tested hand-carried stair descent devices, three staircase widths, and two urgency conditions (urgent and non-urgent). The experiment was blocked on the three staircase widths which were selected based upon NFPA 101-2009 code describing staircase widths based on occupant load. Specifically, this study evaluated stair descent tasks performed under the following stair case widths: 0.91 m (building occupancy $<$ 50), 1.12 m (building occupancy $<$ 2000), and 1.32 m (approximates the 1.42 m required for $>=$2000 occupants). Within each staircase width, the sequence of stair descent devices was randomized. The sequence of "urgent" versus "non-urgent" conditions with the stair descent devices was counter-balanced across participants. For comparison purposes, an extra condition was included in which a manual underarm carry was performed on the 1.12 m wide staircase under an urgent condition. Pilot testing suggested that this carry was most physically demanding. Therefore, to minimize participant fatigue, the manual carry was only performed on the medium width stairs and as an urgent condition.

In each experimental condition, participants descended two flights of stairs and proceeded through two landings. As they performed this task, dependent measures were obtained that included task performance measures, muscle recruitment, spine kinematics, and physiologic demands. Task performance measures were comprised of overall task duration and stair descent velocity. Muscle recruitment was assessed using surface electromyographic (EMG) signals sampled bilaterally from the Erector Spinae, Latissimus Dorsi, Deltoid, and Biceps muscles. Spine kinematics were assessed using a Lumbar Motion Monitor (LMM) (Chattanooga Group, Chattanooga, TN, USA). Physiological demands were obtained by sampling the heart rate and ratings of perceived exertion (Borg Scale) at the completion of each condition. Usability assessments data were obtained from post-study interviews.

2.3. Apparatus

The three selected hand-carried devices (Fig. 1) represent different design approaches that have been developed to transport individuals who are injured or who have ambulatory disabilities down multiple flights of stairs. The "extended handle" stair chair (Stair Pro 6250, Stryker, Kalamazoo, MI) was selected to represent a common stair chair design found on FF/EMS vehicles. This chair allowed the lead person to walk down the stairs facing forwards. The "basic" stair chair (Junkin, JSA-800-CS, Louisville, KY) was selected because this chair was narrower than the extended handle stair chair which would potentially be advantageous for use on narrow staircases. The third device was a fabric seat with sewn in handles (Comfort Carrier, Broadened Horizons-GimpGear, Maple Grove, MN). The relevant dimensions that affect how these three devices are used are provided in Fig. 2.

The staircase was 1.32 m wide and the corresponding landings were 1.32 m deep. The width of the staircase and the depth of the landing were narrowed using tape lines and partitions placed on the landings to simulate the 0.91 and 1.12 staircase widths. The rise and run of each step was 17 cm and 28 cm, respectively.

EMG data were obtained using a Delsys (Boston, MA) wireless EMG system sampled at 1000 Hz. Heart rate data were sampled using a chest-band transmitter unit that displayed data on a wristwatch (Polar Electro, Inc., Lake Success, NY). The participants were polled as to their perceived level of effort at the completion of each stair descent using a 10-point Borg-type rating system (Borg,