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Analysis of foot clearance in firefighters during ascent and descent of stairs

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ABSTRACT

Slips, trips, and falls are a leading cause of injury to firefighters with many injuries occurring while traversing stairs, possibly exaggerated by acute fatigue from firefighting activities and/or asymmetric load carriage. This study examined the effects that fatigue, induced by simulated firefighting activities, and hose load carriage have on foot clearance while traversing stairs. Landing and passing foot clearances for each stair during ascent and descent of a short staircase were investigated. Clearances decreased significantly ($p < 0.05$) post-exercise for nine of 12 ascent parameters and increased for two of eight descent parameters. Load carriage resulted in significantly decreased ($p < 0.05$) clearance over three ascent parameters, and one increase during descent. Decreased clearances during ascent caused by fatigue or load carriage may result in an increased trip risk. Increased clearances during descent may suggest use of a compensation strategy to ensure stair clearance or an increased risk of over-stepping during descent.

1. Introduction

Firefighting is an inherently dangerous occupation. Numerous factors associated with firefighting result in increased risks for injuries: traversing obstacles on the fireground (e.g. stairs), the highly demanding workloads of the fireground, and carrying heavy tools and equipment (e.g. asymmetric carriage of firefighting hose over one shoulder). Slip, trip, and fall (STF) injuries are the second leading cause of minor injuries on the fireground (20%) and the leading cause of moderate to severe injuries in firefighters (28%) (Karter, 2012). Indeed, STF injuries are the only cause of fireground injury which have a higher percentage of moderate to severe injuries than minor injuries on the fireground (Karter, 2012).

As a common obstacle on the fireground, firefighters routinely traverse stairs before, during, and following fire suppression operations. Typical examples include traversing a short stair case (about 3 steps) at the entrance to a residence, and ascending/descending several flights of stairs to reach the fire floor in high rise buildings. Results from a survey of 148 firefighters indicated stairs were involved in nearly 10% of STF injuries (Petrucci et al., 2012).

There has been no research examining the risks of slips, trips and falls by firefighters on stairs; however stair-related risk of STFs have been studied in high-risk populations including persons with degenerative neurological diseases (Di Fabio et al., 2007) and in the elderly (Hamel et al., 2005). Di Fabio et al. (2007) found lower clearance during ascent in subjects with more severe impairments, while Hamel et al. (2005) reported that young adults increased their foot clearance during descent when ambient light was decreased to ensure stair clearance, but that older adults did not similarly adapt their foot clearance. Bergmann et al. (2012) examined the effects of lower-limb fatigue (after a maximal recumbent cycling protocol) on stair performance in healthy adults and found that overall joint range of motion was not influenced post-fatigue. However, firefighters experience whole-body fatigue during firefighting activities, and examination of foot clearances over stair edges following simulated firefighting activity would provide a better understanding of how changes in movement control relate to increased STF risk.

Acute fatigue is common during firefighting tasks (Smith et al., 1996). Heat stress contributes to the onset of fatigue and has been shown to negatively impact firefighters by altering physiological parameters (Rowell, 1974; Smith et al., 1996, 2001; Horn

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et al., 2011), decreasing hydration levels (Horn et al., 2012), and decreasing the delay before muscular fatigue sets in Gonzalez-Alonso et al.(1999). Fatigue can negatively impact postural sway (Nardone et al., 1997) and may contribute to increased STF risk in firefighters.

While most of these data were collected from activities performed within a live-fire environment, there is a current need in fire service research to determine how best to generate acute fatigue in controlled laboratory environments which simulate firefighting environments (Barker, 2005). Live-fire testing simulates temperature, humidity, and visibility conditions through a very large controlled wood-burning fire within a specially constructed burn building. Live-fire testing has high costs and high risks, as well as risk of damage to sensitive equipment; thus limiting data collection opportunities. Temperature-controlled environmental chambers allow for safe, controlled data collection but can be limited in their ability to replicate the thermal and visibility conditions of the fireground.

While conducting these strenuous activities, firefighters commonly carry asymmetric loads, such as sections of fire hose, tools, or extinguishers. For example, responses in high-rise structures will often involve the carriage of a hose load (about 7.5 m of folded fire hose) carried over one shoulder resulting in a medial-lateral asymmetric load distribution. However, studies on asymmetric loading have focused mostly on the general population. In these works, medial-lateral asymmetric load carriage has been shown to impact gait kinematic parameters on both the loaded and unloaded sides of the body (DeVita et al., 1991; Zhang et al., 2010; Ozgul et al., 2012). Ozgul et al. (2012) suggested that habitually carrying a backpack weighing 15% of body weight on one shoulder may result in changes in knee biomechanics that could contribute to joint degradation. Zhang et al. (2010) investigated the impact of carrying a dumbbell weighing 10% or 20% of body weight in one hand and found increased medial-lateral trunk bend and ground reaction force asymmetry during walking than without load carriage. DeVita et al. (1991) found that asymmetrical load carriage of 20% of body weight carried in a sidepack increased the hip and knee extensor moments of the unloaded leg, while decreasing moments on the loaded side. The impact of asymmetric load carriage on stair ascent/descent could lead to compromised performance on the fireground and increased injury risk, an issue that has not previously been studied.

The specific aims of this study were to evaluate foot clearance during stair ascent and descent with emphasis on the effects of (1) acute fatigue and (2) load carriage inducing medial-lateral asymmetry. A secondary aim was to assess different firefighter exercise testing protocols to help inform standards for experimental protocols.

2. Methods

2.1. Overall study design

This research focuses on one aspect of a larger study involving a six station obstacle course (Fig. 1) that was completed before and after three different testing protocols designed to replicate workloads associated with firefighting activities. Horn et al. (2015) provides a detailed description of the three protocols that include: (1) walking on a treadmill (4.5 km/h at a 2.5% incline) in an environmental chamber (47 °C, 30% humidity) (ECTM), (2) simulated firefighting tasks in an environmental chamber (47 °C, 30% humidity) (ECFF), and (3) simulated firefighting tasks in a burn building with live-fire (135 °C at 30 cm from ceiling, 85 °C at 120 cm from the floor, 30 °C at 30 cm above the floor, very low humidity) (BBFF). Simulated firefighting tasks consisted of four activities, where a single activity (climbing stairs, advancing a weighted hoseline, searching a room, pulling down a ceiling) was performed for 2 min, followed by a 2 min rest period. Each of the three protocols was 14 min long. Trials were presented in a counter-balanced order to minimize any potential familiarization effects with the simulated firefighting tasks. At least 24 h prior to beginning the first simulated firefighting protocol, subjects completed a baseline session where they were familiarized with all of the exercise and assessment protocols as well as the personal protective equipment (PPE) and self-contained breathing apparatus (SCBA) that they were to wear for the study.

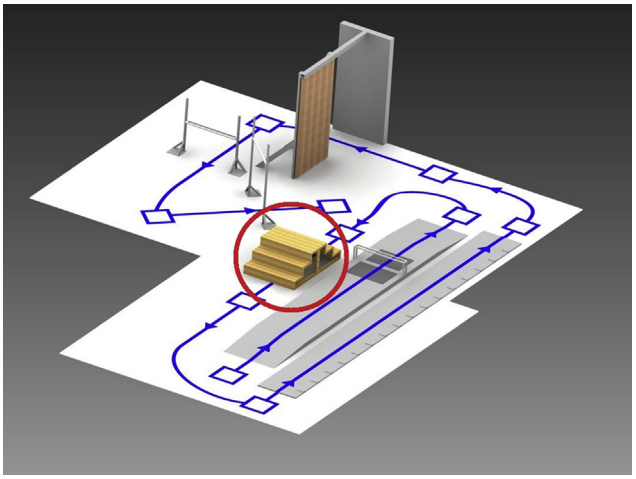

Fig. 1. 3D rendering of obstacle course with six stations.

All activities were performed in full NFPA 1971 (2013) structural firefighting protective equipment (turnout coat and pants, boots, gloves, Nomex hood, and helmet; Globe Manufacturing, Pittsfield, NH) with a NFPA 1981 (2013) 45-min SCBA air pack (Firehawk M7, MSA Co., Cranberry Township, PA). A full SCBA bottle was always utilized during pre- and post-exercise data collection.

2.2. Stair traversal station

This manuscript focuses on the second station of the obstacle course, which required firefighters to traverse a short stairway, simulating the typical front steps that a firefighter might navigate entering and exiting a single family home. Subjects crossed over a three step wooden-frame stairway (1.2 m wide, 18 cm rise, 28 cm run), ascending one side and descending the opposite, always facing forward. The top surface was the equivalent of two steps deep (56 cm). Participants started the station 60 cm from the start of the stairway and ended 91 cm from the final step.

Subjects were instructed to cross the stair obstacle at a pace that he or she would use on the fireground, without running. Subjects completed the obstacle twice wearing full firefighting PPE without supplemental load carriage (no Hose condition), and twice carrying an 11.3 kg hose load, which was always carried on the right shoulder (Hose condition). Rest was allowed between each trial.

2.3. Quantifying stair clearances

To characterize risk of trip or slip incidence while traversing stairs, toe and heel clearances over the edges of the stairs were calculated using three-dimensional motion capture data recorded at 200fps (OQUS 100, Qualisys AB; Sweden). Reflective passive markers were placed on the boot in the vicinity of the heel, first metatarsal, fifth metatarsal, and on the tip of the boot. Using