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Effects of air bottle design on postural control of firefighters

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ABSTRACT

The purpose of this study was to investigate the effect of firefighter's self-contained breathing apparatus (SCBA) air bottle design and vision on postural control of firefighters. Twenty-four firefighters were tested using four 30-minute SCBA bottle designs that varied by mass and size. Postural sway measures were collected using a forceplate under two visual conditions (eyes open and closed) and two stance conditions (quiet and perturbed stances). For perturbed stance, a mild backward impulsive pull at the waist was applied. In addition to examining center of pressure postural sway measures for both stance conditions, a robustness measure was assessed for the perturbation condition. The results suggest that wearing heavy bottles significantly increased excursion and randomness of postural sway only in medial-lateral direction but not in anterior-posterior direction. This result may be due to stiffening of plantar-flexor muscles. A significant interaction was obtained between SCBA bottle design and vision in anterior-posterior postural sway, suggesting that wearing heavy and large SCBA air bottles can significantly threaten postural stability in AP direction in the absence of vision. SCBA bottle should be redesigned with reduced weight, smaller height, and COM closer to the body of the firefighters. Firefighters should also widen their stance width when wearing heavy PPE with SCBA.

1. Introduction

Falls and loss of balance on the fireground lead to over 11,000 injuries per year or more than 25% of all fireground injuries (Karter and Molis, 2008; Karter, 2009). Firefighter's stability and balance has been shown to be influenced by their personal protective equipment (PPE) (Punakallio et al., 2003; Sobeih et al., 2006) which can include bunker coat and pants, boots, hood, gloves, helmet, and a self-contained breathing apparatus (SCBA). The SCBA consist of a face piece, back pack, regulator, and pressurized air bottle. Wearing firefighting PPE with SCBA has been found to significantly impair postural balance (Punakallio et al., 2003).

Previously, we investigated the effects of different SCBA air bottle designs (varying bottle mass and size) on gait performance of firefighters by examining kinetic and kinematic gait parameters, while walking over obstacles and at different walking speeds (Park et al., 2010). We found that the mass of the air bottle significantly affected gait behavior. Specifically, heavier SCBA bottles increased anterior-posterior and vertical ground reaction forces, and increased incidence of contact of the trailing limb when walking over a stationary obstacle, which may increase possibility of slip, trip and falls. In the current study, we investigated the effect of SCBA air bottle design on the standing balance of firefighters.

Several studies have investigated the effect of load-carriage on the postural stability of military personnel, adults and children. It has been reported that load-carriage caused increased excursion of the center of pressure (COP) and larger ground reaction forces, indicating that adding a load on the back deteriorates postural stability (Birrell et al., 2007; Schiffman et al., 2006). Wearing heavy and bulky personal protective equipment was found to worsen functional balance of firefighters (Hur et al., 2013). Increasing the

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backpack load for school children was found to increase forward trunk lean angle, likely as compensation for the induced postural instability of the greater weight (Singh and Koh, 2009). In addition to the weight of the backpack, the location of the backpack center of mass (COM) also affects posture, with placement of the backpack COM close to the body COM reducing energy cost (Knapik et al., 1996).

Wearing a weighted backpack or SCBA may influence individual's ability to respond effectively to a perturbation. Perturbed stance parameters may also provide useful information about the stability or robustness of the postural control system since falls are often initiated by unexpected perturbations. We recently proposed a new metric to assess robustness of the postural control system to a mild backward impulsive perturbation at the waist (Hur et al., 2010). The robustness metric assesses how well a postural control system can resist against unexpected perturbation. This metric may provide useful insight about fall risks of firefighters on the fireground since firefighters often fall due to unexpected perturbations on the fireground.

Postural stability may also be hampered by poor vision. The vision of a firefighter is often compromised by wearing the SCBA facepiece, fogging of the facepiece caused by transitioning between different temperature and moisture conditions, or by smoke inside or outside of a burning structure. Generally, postural steadiness of middle-aged healthy adults decreases under reduced vision (Cornilleau-Peres et al., 2005) and the postural sway of firefighters with eyes closed condition has been shown to increase compared to normal vision (Punakallio et al., 2003).

At present the effects of mass and size of SCBA air bottle and their interactions with vision on postural sway and robustness of firefighters to mild balance perturbations has not been investigated. The objective of the present study was to examine how mass and size of an SCBA air bottle affects postural sway and postural robustness to external perturbation of firefighters and how these parameters interact with vision. It is hypothesized that both heavy and large SCBA and removal of vision will worsen postural sway and robustness. It is further hypothesized that no vision condition will more severely deteriorate postural sway and robustness.

2. Method

2.1. Participants

Twenty-four young male firefighters (age 26 ± 5 years, height 177 ± 8 cm, weight 86 ± 19 kg, and firefighting experience 5.6 ± 4.3 years (range 1–14 years)) were recruited from Illinois Fire Service Institute (IFSI) training events and local fire departments. Twenty-two firefighters classified themselves as volunteer, and two as career firefighters. The subjects reported no history of neurological, postural disorders or vision problems. Informed consent was given by all subjects and the study was approved by the University of Illinois Institutional Review Board. Six of the 24 subjects (both volunteers) were excluded in this analysis due to incompleteness of data.

2.2. Air bottle designs

We tested four different “30-minute” air bottles. The designs consisted of an aluminum bottle (AL), a carbon fiber bottle (CF), a fiberglass bottle (FG), and a specially redesigned bottle (RD) (Fig. 1). The aluminum bottle (DOT# E6498-2216, Scott) is commercially-available and is representative of commonly used relatively low-cost, low pressure (2216 psi), heavy and large bottles. The carbon fiber bottle (DOT# E10915-4500, Luxfer) is also commercially-available and represented relatively expensive, high pressure (4500 psi), light and small bottles. The fiberglass bottle (DOT# 8059-4500, ISI) was similar in size to the CF bottle, but was modified to have the same mass as the AL bottle, in order to examine the effect of mass and size independently. To examine the effect of lowering the center of mass location, a “redesign” bottle was constructed. The RD bottle was constructed from a high pressure “60-min” (2.49 m^3) carbon fiber bottle (DOT# E10915-4501, Luxfer) that was cut to so that the RD bottle had the same air volume and mass of the CF bottle. As a result, the RD bottle had a lower center of mass (COM) location relative to the CF bottle on the firefighter's back by approximately 7.6 cm. Cutting the larger diameter “60-minute” CF bottle for the RD bottle resulted in a posteriorly-directed increase of the RD bottle COM location by

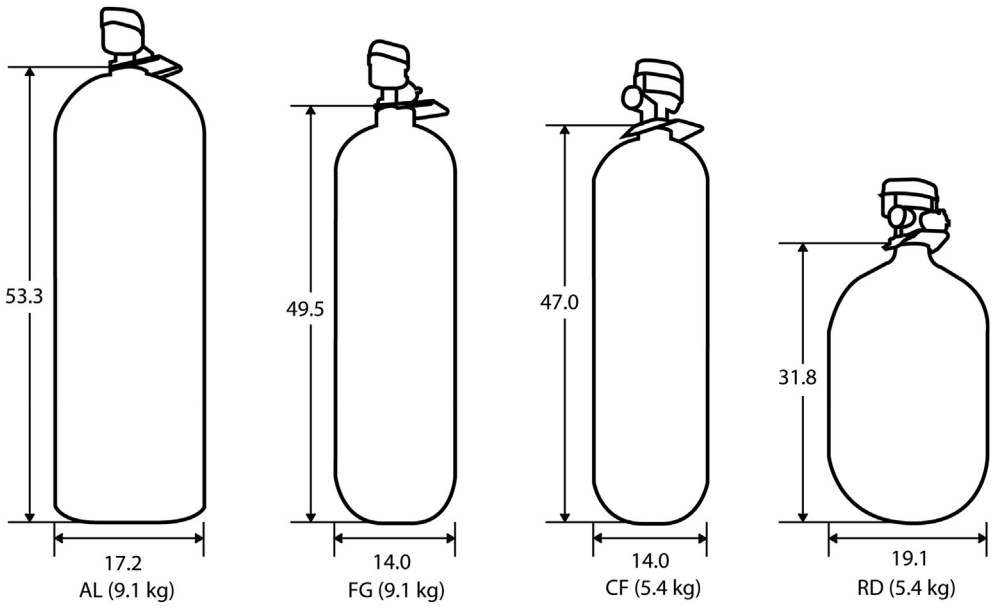

Fig. 1. SCBA air bottle masses and dimensions (cm) for Aluminum (AL), Fiberglass (FG), Carbon fiber (CF) and Redesigned (RD) bottles. Stated mass represents bottle mass when full of air.