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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

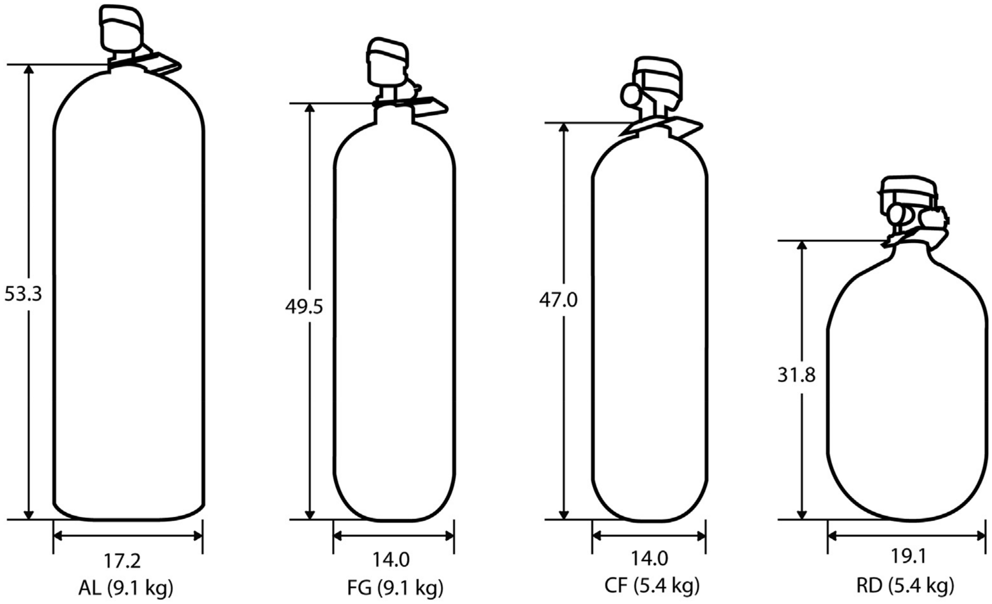

Fig. 1. SCBA air bottle masses and dimensions (cm) for Aluminum (AL), Fiberglass (FG), Carbon fiber (CF) and Redesigned (RD) bottles. Stated mass represents bottle mass when full of air.

2.6 cm compared to that of the CF bottle. We chose this redesign in part because a 60-minute diameter mandrel could directly be used to create shorter bottles. For safety reasons, we used unpressurized bottles in this study. To compensate for the mass of air in a fully-charged bottle, we attached steel rods weighing 1.7 kg into the center of all four bottles.

2.3. *Experimental procedure*

All participants brought and wore their own bunker coat, pants, and boots assigned by his home department. They were provided a helmet (Lite Force Plus, Morning Pride) and SCBA pack (50i SCBA, Scott). The SCBA face piece, regulator, and low pressure line were not used during the experiment.

Participants were asked to stand quietly with both feet on a large force platform (AMTI, model BP600900; Watertown, MA) in a self-selected, comfortable stance with arms crossed at the chest while looking at a picture placed at eye level 3 m from the subject (Fig. 2). The location of each participant's boots was traced to ensure the same foot positioning for the same air bottle condition. In order to avoid inconsistencies in the data at transitions, data collection began 2 s after the participant was informed that the trial started. All force platform data were sampled at 1000 Hz. Force platform data were used to compute COP measures in both anterior-posterior (AP) and medial-lateral (ML) directions.

Participants were instructed to either open or close their eyes during data collection. The order of visual condition presentation was randomized across subjects; however all subjects performed either all eyes open trials or all eyes closed trials first. For each visual condition, two different perturbation conditions (unperturbed and perturbed stances) were applied to subjects. The total number of trials per visual condition were 10 consisting of 3 unperturbed and 7 perturbed trials. Both unperturbed and perturbed standing trials were combined and presented in randomized order. For the unperturbed stance, participants stood quietly on a force platform for 60 s. For perturbed stance, a mild impulsive backward tug was applied to the SCBA pack near the subjects' waist. Timing of the perturbation was randomized between 10 and 50 s after the start of a trial so that the subject was not given cues about if and when the tug would occur during a trial. Data collection was stopped 10 s after a tug because computation of sensitivity function in frequency domain required data length worth of 5 s before and 5 s after the tug. The tug was delivered by a custom-made device via a loose tether to the pack such that the normal postural sway was unhindered before and after the tug (Fig. 2). The impulse perturbation was generated by a pneumatic cylinder that was controlled by an electronic timer. After the brief tug, the mechanism allowed the tether to quickly slacken, allowing the subject to adjust to an upright posture. The perturbation magnitude was designed to elicit only a sway response about the ankles. Tug force was measured from a load cell (PCB Piezotronics, model 208C02; Depew, NY).

2.4. *Data analysis*

Three postural sway assessment techniques were used to analyze the unperturbed stance trials: traditional summary COP descriptive measures (Prieto et al., 1996); stabilogram diffusion analysis (SDA) (Collins and De Luca, 1993) which describes the diffusion behavior of the COP with respect to time; and invariant density analysis (IDA) (Hur et al., 2012) which models the reduced-order dynamics of the human postural control system. This relatively new measures of IDA try to capture the hidden dynamic structure from stochastic and random behavior of COP fluctuation using Markov chain. Measures in both the AP and ML directions were examined. The traditional measures (Prieto et al., 1996) included maximum distance (*MaxDist*), standard deviation (*SD*), and range (*Range*) of the COP. The SDA measures (Collins and De Luca, 1993) included short-term diffusion coefficients (*DS*), long-term diffusion coefficients (*DL*), short-term scaling exponent (*HS*), and long-term scaling exponent (*HL*). The IDA measures (Hur et al., 2012) included peak probability (*Ppeak*) which describes the probability that the COP will visit a certain state, the average distance from the COP distribution centroid (*MeanDist*), the distance from the centroid to which there is a 95% probability of containing the entire COP distribution (*D95*), the 2nd eigenvalue (*EV2*) of the transition matrix that contains the probabilities by which the movement of COP in the next step is determined, and the Shannon entropy (*Entropy*) which describes the randomness or uncertainty of COP movement (Shannon, 1948).

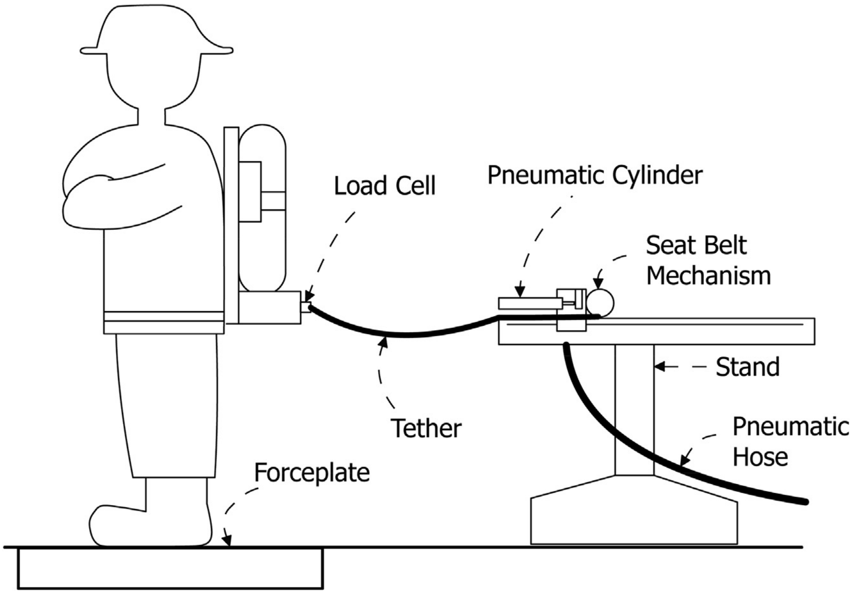

Fig. 2. Experimental setup. The participant stood on a force platform, which recorded the resultant center of pressure under both feet. A load cell recorded the impulse force that was transmitted through a tether attached to the SCBA pack. The perturbation was created by activating a pneumatic cylinder and seatbelt carriage.

Robustness of the postural control system in the AP directions was evaluated for perturbed stance trials by the method described in Hur et al. (2010). This method determines the sensitivity function to external perturbation for the postural control system in frequency domain. The sensitivity function describes how responsive a system is to small perturbations in the system; larger values indicate reduced robustness or decreased relative stability of the system. Robustness was quantified by recording the inverse of the maximum magnitude of the sensitivity function (*1/MaxSens*) in response to an impulse perturbation (a mild backward tug). In particular, sensitivity function was computed as in the following equation (Eq. (1)).

$$S(j\omega) = \frac{G_{F\theta}(j\omega)}{G_{FF}(j\omega)} \tag{1}$$

where $G_{FF}(j\omega)$ is the auto power spectrum of input perturbation (F), and $G_{F\theta}(j\omega)$ is the cross power spectrum between the input perturbation (F) and output lean angle (θ).

2.5. Statistical analysis

A two-way repeated-measures analysis of variance (ANOVA) was used on each measure to examine whether bottle design (AL, FG, CF and RD) and vision (eyes open and eyes closed) affected postural sway (traditional measures, SDA, IDA) and robustness (*1/MaxSens*). Once significant main effect and/or interaction effect were found, post hoc tests were used with the LSD approach (Fisher's least significant difference). The level of significance was set to $\alpha = 0.05$. Statistical analyses were run on SPSS (SPSS Inc., Chicago, IL; v20).

3. Results

Heavy bottles (AL, FG) significantly increased postural sway and randomness of COP fluctuation in the ML direction, compared with light bottles (CF, RD). Heavy bottles increased traditional measures of SD_{ML} and $Range_{ML}$, SDA measure of DL_{ML}, and IDA measures of $MeanDist_{ML}$, $D95_{ML}$, $EV2_{ML}$, and $Entropy_{ML}$ by 30%, 23%, 103%, 48%, 44%, 0.3%, and 9% respectively, and decreased IDA measure of $Ppeak_{ML}$ by 17% (Table 1). Repeated-measures ANOVA indicated significant main effects for bottle design in the following ML-directed COP measures: SD_{ML} ($F(3,17) = 5.55$, $p = 0.008$), $Range_{ML}$ ($F(3,17) = 3.57$, $p = 0.036$), DL_{ML} ($F(3,17) = 3.86$, $p = 0.028$), $Ppeak_{ML}$ ($F(3,17) = 10.20$, $p < 0.001$), $MeanDist_{ML}$ ($F(3,17) = 7.05$, $p = 0.003$), $D95_{ML}$ ($F(3,17) = 5.47$, $p = 0.008$), $EV2_{ML}$ ($F(3,17) = 3.25$, $p = 0.048$) and $Entropy_{ML}$ ($F(3,17) = 18.57$, $p < 0.001$). Post-hoc tests revealed that heavier bottles (AL and FG) resulted in significantly increased excursion and random movement of postural sway in the ML direction (Table 1). No significant effects were found in the AP direction.

Vision was also found to significantly affect postural sway (Table 1). Repeated-measures ANOVA indicated a significant main effect for visual condition in both AP and ML directions: $MaxDist_{AP}$ ($p < 0.001$), $MaxDist_{ML}$ ($p = 0.006$), SD_{AP} ($p = 0.002$), SD_{ML} ($p = 0.011$), $Range_{AP}$ ($p < 0.001$), $Range_{ML}$ ($p = 0.001$), $Ppeak_{ML}$ ($p = 0.046$), $MeanDist_{ML}$ ($p = 0.019$), $D95_{ML}$ ($p = 0.016$), $Entropy_{AP}$ ($p = 0.016$) and $Entropy_{ML}$ ($p = 0.001$). Specifically, removal of vision significantly increased the excursion and random behavior of postural sway in both AP and ML directions (Table 1).

An interaction between bottle design and vision (Table 1) revealed a significant effect for $D95_{AP}$ ($F(3,17) = 4.57$, $p = 0.016$). Post hoc test revealed that $D95_{AP}$ was significantly greater without vision compared to with vision only for AL bottle ($p = 0.01$), suggesting that AP postural sway of participants who wore heavy and large bottles was significantly amplified without vision (Fig. 3).

Neither bottle design nor visual condition was found to affect the robustness of the postural control system in response to an AP-directed perturbation (Table 1). Furthermore, no interaction effect on robustness of participants was found between bottle design and visual condition. There were no significant differences in stance widths measured from foot tracing for each bottle condition.

Table 1

Measures of postural sway and robustness. Postural sway measures include traditional measures (TRAD), and IDA measures. Robustness measure includes *1/MaxSens*. Values represent mean (standard error). Superscript denotes significant differences from indicated main effect condition ($p < 0.05$). Interaction represents the p-value for the interaction Bottle × Vision.

Parameter		Bottle				Vision		Interaction p-value
		AL (A)	FG (B)	CF (C)	RD (D)	EO (E)	EC (F)	
TRAD	$MaxDist_{AP}$	19.61 (1.56)	19.18 (1.67)	18.44 (1.36)	17.86 (1.26)	16.88^{F} (1.11)	20.72^{E} (1.54)	0.31
	$MaxDist_{ML}$	8.65 (1.00)	9.18 (1.37)	7.40 (0.85)	7.17 (0.73)	7.35^{F} (0.73)	8.86^{E} (1.13)	0.77
	SD_{AP}	6.38 (0.55)	6.34 (0.57)	6.01 (0.56)	5.83 (0.41)	5.68^{F} (0.44)	6.60^{E} (0.53)	0.54
	SD_{ML}	2.75^{CD} (0.37)	2.82^{CD} (0.47)	2.17^{AB} (0.29)	2.10^{AB} (0.23)	2.22^{F} (0.26)	2.69^{E} (0.39)	0.51
	$Range_{AP}$	34.45 (2.68)	33.67 (2.97)	31.81 (2.33)	31.00 (2.12)	29.48^{F} (1.98)	35.98^{E} (2.63)	0.51
	$Range_{ML}$	14.88^{CD} (1.74)	15.72^{CD} (2.34)	12.69^{AB} (1.48)	12.18^{AB} (1.20)	12.45^{F} (1.29)	15.28^{E} (1.92)	0.72
SDA	DS_{AP}	18.45 (2.34)	17.12 (3.28)	15.75 (2.19)	16.14 (2.30)	11.83^{F} (1.47)	21.89^{E} (2.87)	0.39
	DS_{ML}	4.09 (0.86)	4.76 (1.50)	3.45 (0.67)	3.19 (0.52)	3.11^{F} (0.60)	4.63^{E} (0.99)	0.41
	DL_{AP}	2.83 (0.50)	2.97 (0.57)	2.72 (0.61)	2.43 (0.42)	2.58 (0.49)	2.90 (0.44)	0.93
	DL_{ML}	0.61^{CD} (0.16)	0.67 (0.27)	0.31^{A} (0.17)	0.32^{A} (0.08)	0.37 (0.11)	0.58 (0.20)	0.44
	HS_{AP}	0.86 (0.01)	0.85 (0.01)	0.85 (0.01)	0.85 (0.01)	0.83^{F} (0.01)	0.87^{E} (0.01)	0.86
	HS_{ML}	0.80 (0.01)	0.81 (0.01)	0.80 (0.01)	0.80 (0.02)	0.79^{F} (0.01)	0.81^{E} (0.01)	0.08
	HL_{AP}	0.21 (0.02)	0.22 (0.02)	0.24 (0.02)	0.22 (0.02)	0.24^{F} (0.02)	0.20^{E} (0.01)	0.77
	HL_{ML}	0.23 (0.02)	0.21 (0.02)	0.19 (0.02)	0.21 (0.02)	0.22 (0.02)	0.21 (0.02)	0.41
IDA	$Ppeak_{AP}$	0.03 (0.00)	0.04 (0.00)	0.04 (0.00)	0.04 (0.00)	0.04 (0.00)	0.03 (0.00)	0.20
	$Ppeak_{ML}$	0.08^{CD} (0.01)	0.09^{CD} (0.01)	0.10^{AB} (0.01)	0.10^{AB} (0.01)	0.10^{F} (0.01)	0.09^{E} (0.01)	0.45
	$MeanDist_{AP}$	5.46 (0.58)	6.64 (1.42)	4.93 (0.48)	4.79 (0.36)	4.76 (0.41)	6.15 (0.76)	0.56
	$MeanDist_{ML}$	2.36^{CD} (0.31)	2.66^{CD} (0.48)	1.82^{AB} (0.24)	1.76^{AB} (0.19)	1.90^{F} (0.22)	2.40^{E} (0.35)	0.29
	$D95_{AP}$	13.60 (1.45)	13.11 (1.66)	12.15 (1.07)	11.82 (1.01)	12.03 (1.12)	13.31 (1.24)	**0.02**
	$D95_{ML}$	5.94^{CD} (0.83)	6.44^{CD} (1.10)	4.32^{AB} (0.55)	4.30^{AB} (0.49)	4.69^{F} (0.54)	5.81^{E} (0.84)	0.26
	$EV2_{AP}$	0.999 (0.000)	0.999 (0.000)	0.999 (0.000)	0.999 (0.000)	0.999 (0.000)	0.999 (0.000)	0.21
	$EV2_{ML}$	0.996^{D} (0.001)	0.996^{D} (0.001)	0.994 (0.001)	0.993^{AB} (0.001)	0.995 (0.001)	0.995 (0.001)	0.62
	$Entropy_{AP}$	5.92 (0.13)	5.86 (0.14)	5.81 (0.12)	5.79 (0.11)	5.76^{F} (0.11)	5.93^{E} (0.12)	0.08
	$Entropy_{ML}$	4.63^{CD} (0.16)	4.62^{CD} (0.17)	4.26^{AB} (0.14)	4.26^{AB} (0.14)	4.32^{F} (0.13)	4.57^{E} (0.16)	0.61
Robustness	*1/MaxSens*	53.63 (0.47)	52.71 (0.67)	53.24 (0.78)	53.71 (0.67)	52.95 (0.57)	53.69 (0.54)	0.53

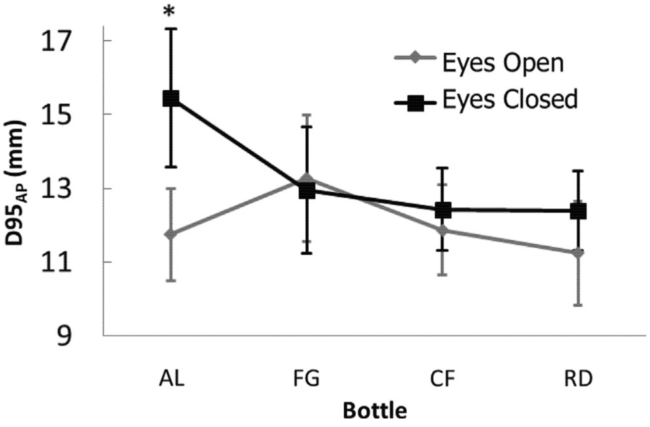

Fig. 3. Interaction between vision and bottle design as a function of distance to 95% probability of containing the COP (*D95*) in AP direction. Error bars indicates standard errors. "*" represents statistical significant effect of vision for a given bottle.

4. Discussion

4.1. Heavy load mass increased excursion and randomness of postural sway

Heavy bottles (AL, FG) significantly increased COP fluctuation in the ML direction, compared with light bottles (CF, RD). Schiffman et al. (2006) found positive linear relationships between mass of the load and the extent of postural sway as measured by traditional COP measures in all directions. Punakallio et al. (2003) reported that wearing firefighting PPE including SCBA significantly increased COP excursions in both AP and ML directions. It has been reported that increased postural sway is a good indicator of increased fall risks among community dwelling elderly adults (Stalenhoef et al., 2002). Therefore, firefighters with heavier mass of SCBA may have higher risk of falling on the fireground.

Wearing heavy bottles also resulted in significant increases in the random behavior (or stochastic behavior) of the COP excursion. A smaller *Ppeak* value implies that the COP excursions tend to diffuse throughout the base of support, as opposed to being concentrated toward the centroid of the COP excursion. In this sense, smaller $Ppeak_{ML}$ values suggest that wearing heavy bottles will cause a greater tendency of the body to fluctuate more in the ML direction. A larger *Entropy* value implies that the COP excursions have greater uncertainty and that longer data windows (or more information) are necessary to understand and predict the steady state behavior of the postural control system (Hur et al., 2012). Increased $Entropy_{ML}$ for heavy bottles suggest that COP excursions in the ML direction are more uncertain and harder to predict, which may imply that the postural control mechanism in the medial-lateral direction is more challenged by heavy bottles (Hur et al., 2012). This result is also supported by $EV2_{ML}$ and DL_{ML}. Increased $EV2_{ML}$ for heavy bottles compared to RD (Table 1) suggests that the convergence rate of the COP distribution to the invariant density is delayed (Hur et al., 2012). Increased DL_{ML} for heavy and large bottle suggests that long-term COP with heavy bottles tended toward instability twice as fast as when wearing the lighter bottles (Collins and De Luca, 1993). It appears that the heavy bottles (AL, FG) tend to challenge the feedback control mechanism such that it takes longer for the control mechanism to keep the COP near equilibrium, which in turn increases convergence time to the invariant density. Therefore, using a heavy bottle may have delayed the feedback control mechanism by taxing the postural control system.

4.2. Heavy load mass affected postural sway only in ML direction

Interestingly, our results showed that increasing the mass of the SCBA air bottle reduces postural stability only in ML direction as indicated by significant increase in COP excursion and randomness (Table 1). Previous research on identification of fall risk factors from force platform data found that mean velocity, mean displacement, and standard deviation in the ML direction were important parameters which can indicate future falls of elderly populations (Baloh and Corona, 1998; Bergland and Wyller, 2004; Bergland et al., 2003; Maki et al., 1994; Piirtola and Era, 2006; Stel et al., 2003). One of the possible reasons for the greater postural sway only in ML direction is that ML postural control mechanism is different from AP postural control mechanism. During quiet stance, AP postural control is mostly mediated by ankle muscles (both dorsi-flexors and plantar-flexors) whereas ML postural control is not due to ankle muscles (Winter, 1995). Most of ML postural control is due to the hip abductors/adductors since ankle invertors/evertors are not strong enough to control ML postural sway when large balancing moments are needed (Day et al., 1993; Winter, 1995). When subjects were wearing heavy SCBA air bottles, it was observed and anecdotally reported that they tended to lean forward (or dorsi-flexed ankle joint) to counterbalance the heavy weight. A more dorsi-flexed equilibrium point of the ankle joint entails elongation of plantar-flexor muscles, which may also stiffen plantar-flexor muscles (Kawakami et al., 2008). Thus, the increased stiffness of their plantar-flexor muscles may have compensated for the destabilizing moments due to heavy bottles in the AP direction only, but not in the ML direction.

Another possible reason for increased postural sway in the ML direction is constant stance width. Stance widths measured from foot tracing did not change significantly for each air bottle condition. Jang et al. (2008) reported that ML postural sway was maintained during pregnancy due to increased stance width. Normal healthy individuals also showed reduced ML postural sway with increasing stance width (Day et al., 1993; Kirby et al., 1987). Increased stance width can stiffen hip abductors/adductors (Day et al., 1993), and thus affectively control ML postural sway. Therefore, no increase of stance width for the heavy bottle condition could have increased postural sway in ML direction.

4.3. Postural control robustness of firefighters was not affected in AP direction

The firefighters' postural control robustness in the AP direction was not affected by either the bottle design or the visual condition. Robustness measure addresses different aspects of postural stability from postural sway measures (i.e., TRAD, SDA IDA). In this study, robustness is used to quantify how well the postural control system can resistively react to a mild impulsive external perturbation applied backward (Hur et al., 2010) whereas postural sway measures reflect how the postural control system stabilizes the persistently destabilizing force due to the SCBA. No changes in the robustness measure to a mild impulsive backward perturbation imply that the increased weight due to wearing PPE with SCBA is actually functioning, to some extent, as a stabilizing factor to a small brief external perturbation so that the small and brief perturbation could not differentiate the weight/size difference among four bottles. Therefore, firefighters may be, to some extent, robust to a small and brief external perturbation in the AP direction. However, on the real fireground, robustness of firefighters can be threatened since the perturbation would be greater, longer and unexpected, which should be further studied in the future studies.

4.4. *Without vision, large bottle with heavy mass may threaten AP postural stability*

What is interesting is that vision significantly interacted with the SCBA air bottle design in the AP direction. Fig. 3 illustrates that $D95_{AP}$ remained almost unchanged for all bottle designs when vision was provided. However, $D95_{AP}$ significantly increased when firefighters were wearing the large and heavy SCBA bottle (AL) and vision was removed, suggesting that AP postural sway of subjects who wore heavy and large bottles significantly increased when subjects closed their eyes (Fig. 3). Only AP direction was affected by vision for AL bottle possibly because postural sway in AP direction is more sensitive to vision compared to ML direction (Day et al., 1993).

Note that size of bottle may not seem to affect the balance of firefighters, based on the main effect of parameters (Table 1). However, the interaction of bottle design and vision for $D95_{AP}$ suggests that size of bottle may also affect the balance of firefighters (Fig. 3). Heavy and smaller bottle (FG) did not affect $D95_{AP}$ for each visual condition. However, heavy and large bottle (AL) affected $D95_{AP}$ for visual condition. This may suggest that elevated COM of bottle worked as a destabilizing factor when postural control system without vision was threatened by heavy bottle. Therefore, wearing heavy and large SCBA air bottles can significantly threaten postural stability in the AP direction if firefighters lose vision. This may imply that the use of heavy and large SCBA air bottles may be detrimental to firefighters on the fire ground.

4.5. *Lowering SCBA COM itself may not enhance postural sway*

Redesigned SCBA bottle (RD) did not improve the postural sway of the firefighters compared to CF. Since the COM of RD was lower than the CF bottle (with the same mass), it was hypothesized that the postural sway for the redesigned bottle would be smaller than the postural sway for the carbon fiber bottle. However, there were no differences between the two bottles. One possible reason is that even though the COM of the redesigned bottle was lowered by 7.6 cm compared with the carbon fiber bottle, the COM of the redesigned bottle also moved 2.6 more posteriorly. Both of the stabilizing and destabilizing moments due to altered COM location might have cancelled each other so that the postural sway due to RD was not affected compared to CF. Therefore, a potential new design of the SCBA air bottle could use the same height as RD but be closer to the body in the AP direction so that the COM minimally induces destabilizing moments. However, in order not to reduce air capacity the redesign may need to be wider in the ML direction and these tradeoffs should be investigated.

4.6. *Limitations*

There are some limitations in this study. This study applied small perturbations to assess robustness of firefighters. To address robustness in a more realistic firefighting situation, greater and unexpected perturbations administered at different levels should be investigated. Robustness of the firefighters' postural control system was measured in AP direction only. Therefore, it would be more useful to study the robustness of the firefighters to the external perturbation with increased perturbation amount in the ML direction. This study had three size conditions and two mass conditions, which required six bottle combinations. However, only four bottles were examined due to the limited availability of bottles. Lastly, this study investigated the effect of SCBA bottle on postural stability of firefighters, which may be different from the fall risk of firefighters. Therefore, the findings in this study should be carefully interpreted for fall risks of firefighters on the fire ground.

5. Conclusions

The results of this study indicate that postural sway was affected by firefighter SCBA bottle mass and vision. Heavy bottles significantly increased the excursion and randomness of postural sway in the ML direction but not in AP direction. This result may possibly be due to stiffening of plantar-flexor muscles and forcing participants to adopt a constant stance width under various bottle conditions. A significant interaction between vision and bottle design for AP postural sway was found, suggesting that wearing heavy and large SCBA air bottles can significantly reduce postural stability in AP direction if firefighters lose vision. This may also suggest that size of SCBA bottles affects postural sway of firefighters. Taken together, these results suggest that use of heavy and large SCBA bottle designs on the fire grounds may put firefighters at greater risk for falls. An important implication of this study is that a SCBA bottle should be redesigned with reduced weight, smaller height, and COM closer to the body of the firefighters. Another implication of this study is that firefighters should widen their stance when wearing heavy PPE with SCBA.

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