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Kiwon Park[a]; Pilwon Hur[a]; Karl S. Rosengren[b]; Gavin P. Horn[ac]; Elizabeth T. Hsiao-Wecksler[a]
[a] Department of Mechanical Science & Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA [b] Department of Psychology, Northwestern University, Evanston, Illinois, USA [c] Illinois Fire Service Institute, University of Illinois at Urbana-Champaign, Champaign, Illinois, USA

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Effect of load carriage on gait due to firefighting air bottle configuration

Kiwon Park[a], Pilwon Hur[a], Karl S. Rosengren[b], Gavin P. Horn[a,c] and Elizabeth T. Hsiao-Wecksler[a]*

[a]*Department of Mechanical Science & Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA;* [b]*Department of Psychology, Northwestern University, Evanston, Illinois, USA;* [c]*Illinois Fire Service Institute, University of Illinois at Urbana-Champaign, Champaign, Illinois, USA*

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The air bottle configuration (mass and size) used with a firefighter's self-contained breathing apparatus may affect functional gait performance and slip/trip/fall risk, contributing to one of the most common and costly fire ground injuries to this population. To examine the potential effect of bottle mass and size on firefighter gait performance, four 30-min air bottle configurations were tested. To quantify biomechanical gait performance, kinetic and kinematic gait data were collected on 24 male firefighters while walking at normal and fast speeds during three conditions (no obstacle, 10 cm or 30 cm stationary obstacle). Bottle mass, obstacle height and walking speed – but not bottle size – were found to significantly impact gait parameters. Ten subjects (42%) contacted the taller obstacle while wearing heavier bottles, suggesting greater risk for tripping. Heavier bottles also resulted in larger forces by the trailing leg in both the anterior–posterior and vertical directions, suggesting greater risk for slipping. These results suggest that increased bottle weight may result in a decrease in gait performance and an increase in fall risk.

Statement of Relevance: Occupations, such as firefighting, often require use of a self-contained breathing apparatus that includes a pressurised air bottle. No systematic assessment has investigated how modest changes in load carriage due to bottle configuration (mass and size) might affect gait behaviour, especially when crossing obstacles. Bottle mass, but not size, was found to decrease gait performance and increase fall risk.

Keywords: firefighting; gait performance; ground reaction force; obstacle crossing; self-contained breathing apparatus

Introduction

One of the leading causes of traumatic injuries among firefighters in the United States is falls and loss of balance on the fire ground. These events lead to over 11,000 injuries per year or more than 25% of all fire ground injuries (Karter 2003, Karter and Molis 2008). Accidents due to falls typically account for the longest work absences for firefighters (Heineman *et al.* 1989, Cloutier and Champoux 2000, Ault 2002). In 2003, a study determined that the mean total worker's compensation claim per slip, trip or fall injury was $8662, which is well above the mean of all claims – $5168 (Walton *et al.* 2003). Thus, slip, trip and fall injuries are not only one of the most common, but also one of the most costly on the fire ground.

Firefighter stability and balance on the fire ground can be influenced by their fire-protective clothing system (Punakallio *et al.* 2003, Sobeih *et al.* 2006). This clothing system typically consists of personal protective equipment (PPE) such as a coat, trousers, boots, hood, gloves and helmet. When firefighters enter an environment that may be immediately dangerous to life and health, the PPE also includes a self-contained breathing apparatus (SCBA) that provides an external air supply. Firefighters are expected to wear their SCBA at each fire (more than 1.5 million fires occurred in the USA in 2007 (Karter and Molis 2008)) and at investigations (smoke, odour, CO, false alarms). The typical components of a SCBA are a back-mounted frame, air bottle, gauges, regulators and a face piece.

Wearing PPE with SCBA has been found to negatively impact physical performance and balance (Louhevaara *et al.* 1985, Kong *et al.* 2010). The addition of the SCBA has been shown to increase fatigue (Louhevaara *et al.* 1985), reduce maximal exercising time and maximal inclined walking speed (Louhevaara *et al.* 1995) and decrease postural and functional balance (Punakallio *et al.* 2003). Heineman *et al.* (1989) found that continual use of SCBA was significantly associated with fall occurrences among firefighters. It is not known, however, how specific aspects of the SCBA, such as the mass and size, contribute to balance and fall-related problems (Heineman *et al.* 1989).

*Corresponding author. Email: ethw@illinois.edu

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Fire departments generally struggle with the type of air bottle to choose, balancing expense with mass and size. Newer lightweight and compact air bottles made from composite materials have a higher cost of ownership (due to the more rigorous testing and rapid replacement schedules); however, older and less costly low pressure steel or aluminium designs are heavier and larger. The goal of this study was to examine whether the reduced mass and size of these composite bottles significantly improves mobility and reduces slip, trip and/or fall risk, thus potentially compensating for their increased cost.

Gait stability has been found to be influenced by the weight of an externally carried load (Tilbury-Davis and Hooper 1999, Birrell *et al.* 2007). In general, studies on gait and load carriage have shown that walking velocity decreases and double support time increases when individuals carry heavier loads (Singh and Koh 2009). To date, the influence of particular air bottle mass and configuration on firefighter gait performance has not been addressed. Based on past research, it is expected that increasing the mass of the air bottle would lead to a decrease in gait performance (Tilbury-Davis and Hooper 1999, Lloyd and Cooke 2000, Birrell *et al.* 2007). Thus, the first objective of this study was to examine the effect of different bottle masses on firefighter gait performance.

Reducing bottle size generally decreases the mass of the bottle, but it also may result in a shift in the magnitude and location of the centre of mass (CoM) of the whole body, which may lead to improved gait behaviour. Lowering the CoM of an external load decreases the moment arm from the load to the hip joint or moment of inertia about the hip joint, which in turn may reduce hip joint resistive moment. Inverse dynamic analysis has shown that greater hip joint moments result in higher ground reaction forces (GRFs) (Winter 2005). It has been hypothesised that lowering the CoM of an external load might lead to reduced GRF. However, to the present authors' knowledge, there have been no studies showing how changes in the CoM of a carried load affects kinetic and kinematic parameters during gait. Therefore, the second objective of the present study was to explore the effects of different bottle sizes on firefighter gait performance.

Two challenging gait conditions that could negatively affect firefighter gait performance are walking at a fast speed and walking over obstacles. Prior research has investigated slip and fall risk of firefighters during walking on a slippery surface (Punakallio *et al.* 2005), showing that slip risk increased with walking speed. However, crossing or moving over objects is one of the most common origins of slip, trip and fall injury on the fire ground (Karter 2003). A decline in the ability to avoid obstacles may result in increased fall risk (Chou *et al.* 2004, Weerdesteyn *et al.* 2005). It is unknown how the SCBA air bottle configuration affects a firefighter's obstacle-crossing ability and fall risk.

Therefore, the purpose of this study was to explore the effects of different bottle configurations (bottle mass and size) on gait performance, as assessed by kinetic and kinematic gait parameters, while walking over obstacles and at different walking speeds. It was expected that reductions in mass and size of the air bottle would improve gait performance, reduce likelihood of slips and trips and reduce fall risk.

Methods

Participants

A total of 24 young male firefighters participated in this study (mean age 26 ± 5 years, height 177 ± 8 cm, weight 86 ± 19 kg and 5.6 ± 4.3 years (range 1–14 years) of firefighter experience). In total, 90% classified themselves as a volunteer and 10% as a career. Since there were only two career firefighters among the subjects, all analyses were performed for all firefighters combined. No subjects reported any previous history of balance and gait impairments, neurological disease or vision problems. Each subject signed an informed consent form approved by the university Institutional Review Board. All subjects completed the experiment successfully, but kinetic data from two subjects were not included in the analysis due to technical problems.

Air bottle configurations

Four 30-min air bottles were tested (Figure 1). The aluminium (AL) bottle (DOT# E6498–2216, Scott)

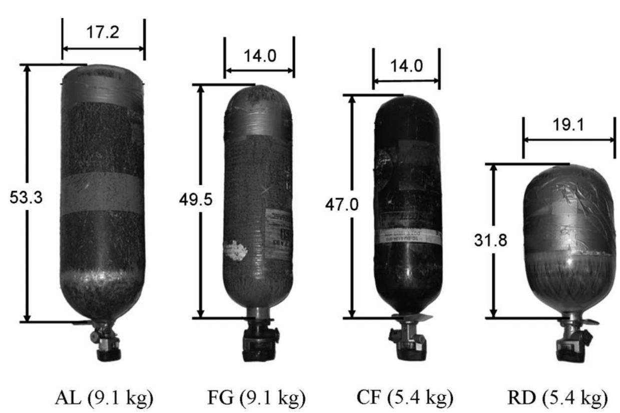

Figure 1. Air bottle dimensions (cm) and weights for aluminium (AL), fibreglass (FG), carbon fibre (CF) and redesigned (RD) bottles. Length dimensions are measured from the pack attachment clip on the bottle regulator to the tip of the bottle.

represented a commonly used and commercially available low pressure (2250 psi) design for a lifetime cylinder that is heavy and large. The carbon fibre (CF) bottle (DOT# E10915–4500; The Luxfer Group, Salford, UK) represented current and commercially available light and small designs. However, these bottles (and the associated refilling infrastructure) are typically more expensive, have limited service lifetimes and require high pressure (4500 psi) compared to AL bottles. A high pressure fibreglass (FG) bottle (DOT# E8059–4500, ISI) with similar size as the CF bottle was constructed to have the same mass as the AL bottle, in order to examine the effect of mass only. To examine the effect of CoM location, a fourth 'redesign' (RD) bottle was constructed. The RD bottle was made from a high pressure 60-min CF bottle (DOT# E10915–4501; Luxfer) that was cut such that the final air volume and mass was similar to the CF bottle. This design resulted in the lowering of the RD bottle's CoM location relative to the CF bottle on the firefighter's back by approximately 7.6 cm. Due to the larger diameter of the 60-min bottle vs. the 30-min bottle, the CoM location moved slightly posterior by approximately 2.6 cm. Thus, the RD bottle provides a light, short design that sat lower on the back. This redesign was selected as it would require less retooling for air bottle manufacturers since a 60-min diameter mandrel could be used to create shorter bottles. This study used unpressurised bottles due to safety issues. Since unpressurised bottles have a significantly reduced mass, the mass for 30 min air (1.7 kg) was added into all four bottles. Steel rods were used to supplement the missing air weight (and added weight for the FG bottle). For each bottle, a rod of uniform cross section was screwed into the valve end of the bottle and aligned along the centre line of the cylinder.

Experimental procedure

The participants walked along a 9.8 m walkway embedded with a 60 × 90 cm^2 force plate (BP600900; AMTI). Subjects wore PPE with one of four SCBA bottles. The subjects were instructed to walk at either of two speeds (normal 'walk at a comfortable pace' or fast 'walk as fast as possible without running') and in obstacle trials step over the obstacle in the path. Three obstacle conditions were tested: no obstacle; 10 cm obstacle; 30 cm obstacle. The lower height obstacle (10 cm) was representative of debris or a fire hose on the fire ground. The 30 cm obstacle was designed to simulate a challenging balance situation but within the range that subjects were well able to walk over (Rosengren *et al.* 1998). Both obstacles were 10 cm in width and 113 cm in length and were constructed using a 1.5 cm diameter polyvinylchloride pipe to create a stick-figure frame that would fall away if contacted to reduce the likelihood of falls during the study (Ramachandran *et al.* 2007). Two trials for each walking speed and obstacle condition were performed. Bottle configuration order was randomised. However, within each bottle configuration, obstacle condition order was always presented as no obstacle, 10 cm obstacle and 30 cm obstacle. For the same obstacle condition, normal speed was presented first and then fast speed. For each condition, practice trials were given to familiarise subjects with the various gait tasks (different speed and obstacle conditions). The starting position during practice trials was adjusted without the subject's knowledge so that, for the no-obstacle condition, one foot cleanly contacted the force plate during the natural course of gait. For the obstacle condition, the starting position was adjusted such that the trailing foot cleanly landed on the force plate. GRF data were sampled at 1000 Hz. Each subject wore his own bunker coat, trousers and boots assigned and fitted by his home department. Helmet (Lite Force Plus; Morning Pride) and SCBA pack (50i SCBA; Scott) were provided (Figure 2). The SCBA

Figure 2. Standard personal protective equipment (PPE) with a self-contained breathing apparatus (SCBA).

face piece and associated hose were not used during the experiment.

Kinematic data were recorded from a six-camera motion capture system (Datastation 460; Vicon Motion Systems, Oxford, UK) at a sampling frequency of 100 Hz. A total of 35 markers were attached to the PPE, helmet, SCBA pack and bottle; however, only the heel and toe markers on the boot and the anterior superior iliac spine markers on left and right sides were used for this analysis. To recognise obstacle position, a marker was attached to each of the top corners of the obstacle.

Data analysis

Six kinematic parameters were collected using similar procedures as in Ramachandran *et al.* (2007): overall gait speed (GS), time in single leg support while crossing the obstacle, anterior–posterior clearance from the obstacle of the trailing toe and leading heel (HCL) at the time of the heel strike of the respective foot, and minimum vertical clearance of the trailing (VCT) and leading (VCL) foot. Overall GS was calculated using temporal data for the midpoint of the anterior superior iliac spine markers on left and right sides over a distance of 3.5 m on the walkway. Single leg support time (SLST) was defined as the time period that the trailing limb was in single leg support while crossing the obstacle. For the no-obstacle trials, SLST was estimated using the comparable foot placement steps near the obstacle position in the obstacle trials. The horizontal clearance for the trailing toe (HCT) was determined as the distance between the obstacle front and the toe marker on the trailing limb at the instant of the heel strike of the trailing foot. HCL was the distance between the obstacle back and the leading heel at the instant of heel strike of the leading foot. VCL and VCT were determined from the minimum distance out of four measurement combinations related to the front or back top edge of the obstacle and the toe or heel of the given foot.

Kinetic gait data consisted of GRF parameters of peak magnitude and impulse. These parameters provide insight into the mechanics of gait and forces acting on the foot (Barela *et al.* 2006, Birrell *et al.* 2007, Barela and Duarte 2008). These parameters were calculated either for the trailing foot during obstacle crossing trials or the foot that landed cleanly on the force plate during the no-obstacle trials. GRF peak magnitude and impulse were analysed for the anterior–posterior, lateral and vertical directions. From the anterior–posterior and vertical GRF data, total peak force and total impulse over the entire gait cycle and also peak force and impulse during both early and late stance were calculated. Impulse is the integral of contact force with regard to time:

$$I = \int F dt, \tag{1}$$

where I is impulse, F is the contact force and t is time. Therefore, impulse provides insight into the effect of both the magnitude of GRF as well as the duration of foot contact time. Both GRF peak magnitude and impulse parameters were normalised by subject's body weight (mass of subject (kg) $\times$ 9.81 (m/s^2)).

The differentiation between early and late stance was defined from the breaking (heel-strike) and propulsion (toe-off) portions of the anterior–posterior and the vertical GRF curve, respectively (Figures 3 and 4). The anterior–posterior GRF curve was divided into early and late stances based on the crossover time that force changes from the anterior to posterior direction. In the vertical GRF, early and late stances were determined based on the local minimum of the data. Since there were no distinct points to determine early and late stance for the lateral GRF, only total peak force and total impulse were recorded for the lateral GRF (Figure 5). Both kinematic and kinetic data used for the analysis were filtered using a forward–backward fourth-order Butterworth filter with cut-off frequencies of 9 Hz for the kinematic data and 8 Hz for the kinetic data.

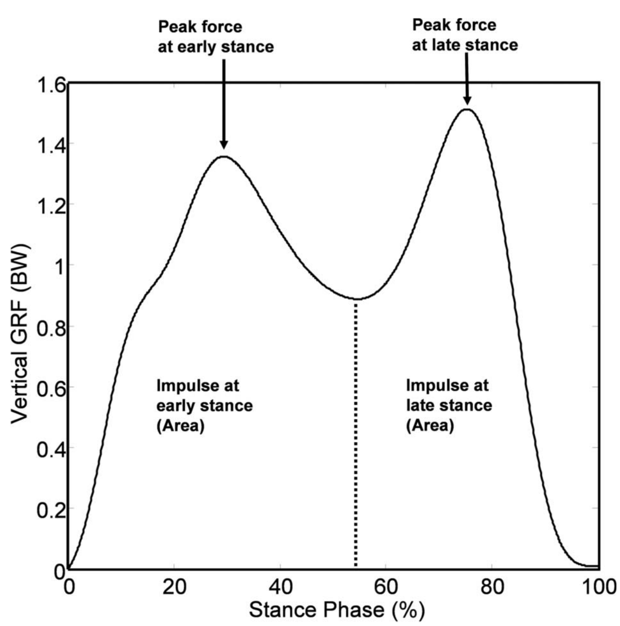

Figure 3. Kinetic gait parameters for vertical ground reaction force (GRF) normalised by body weight (BW).

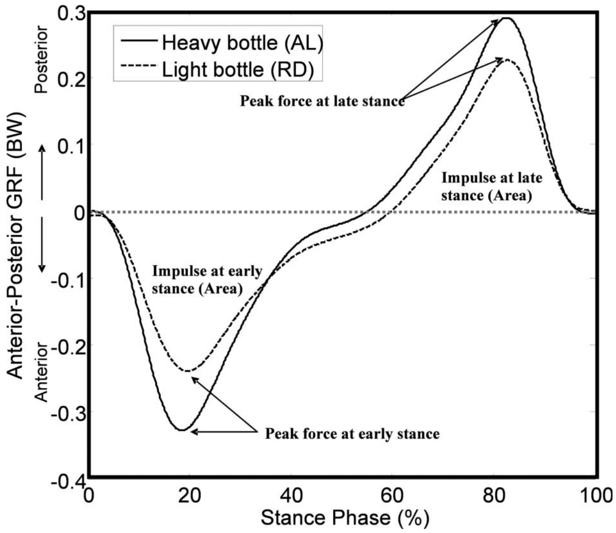

Figure 4. Kinetic gait parameters for anterior–posterior ground reaction force (GRF) normalised by body weight (BW). (Data used for this figure were the no-obstacle trials at normal speed of one subject.) AL = aluminium; RD = redesigned.

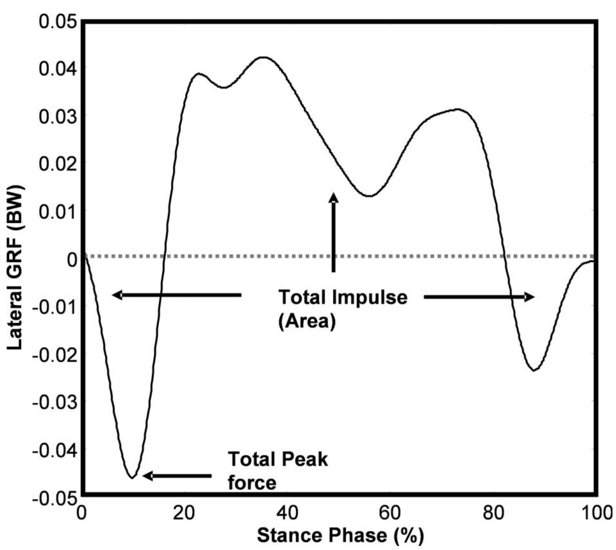

Figure 5. Kinetic gait parameters for lateral ground reaction force (GRF) normalised by body weight (BW).

Statistical analysis

Statistical analyses of all outcome parameters were averaged over two trials per condition. Repeated-measures multivariate ANOVA (MANOVA) tests examined whether bottle configuration, obstacle height and walking speed affected the kinetic and kinematic parameters. Significance was determined at $\alpha = 0.05$. LSD *post-hoc* analyses were used to compare differences among significant treatments. Statistical analyses were run on SPSS (v15; SPSS Inc., Chicago, IL, USA).

Results

Kinematic parameters

The bottle mass, but not size, was found to affect kinematic parameters (Table 1). The MANOVA tests on kinematic parameters indicated a significant main effect for bottle configuration on HCL ($p = 0.047$) and a significant interaction effect for bottle × obstacle height for VCL ($p = 0.034$) (Table 1). *Post-hoc* tests revealed that the lighter CF bottle resulted in significantly longer HCL than the heavier FG bottle. The interaction effect on VCL indicated that subjects wearing all bottles except the RD cylinder had significantly lowered VCL when crossing the higher obstacle (30 cm) than the lower one (10 cm). When participants wore the heavy and large AL bottle, they exhibited the greatest difference between the two obstacle heights (e.g. VCL was 15.8 ± 0.7 cm vs. 12.5 ± 0.8 cm for 10 cm vs. 30 cm obstacle height). Overall GS and single leg stance time during obstacle crossing were not significantly influenced by bottle configuration. No significant interactions between instructed walking speed and bottle configuration were found. Main effects of instructed walking speed and obstacle height statistically affected ($p < 0.05$) all gait parameters except vertical clearances (Table 1). Significant interactions between instructed walking speed and obstacle height were found for GS, VCT and VCL ($p \leq 0.001$).

In total, 10 subjects (42%) hit the 30 cm obstacle during the crossing step while wearing one of the heavier bottles (AL, FG). Seven of these subjects contacted the obstacle during both normal walking speed trials. Three of these seven also hit the obstacle during fast walking. Overall, the 30 cm obstacle was contacted in 28 out of 384 trials (14%). Contact occurrence was even distributed between normal and fast speeds (14 trials each). On the other hand, no obstacle contact was observed for lighter bottles (CF, RD). All obstacle contacts were made by the trailing foot. The 10 cm obstacle was not contacted during any condition.

Kinetic parameters

Similar to the kinematic results, bottle mass significantly affected kinetic parameters, whereas bottle size did not. The MANOVA on the kinetic parameters revealed that bottle configuration had significant main effects on anterior–posterior peak force and impulse and vertical peak force in both early and late stance (Figures 6, 7 and 8, Table 2). Obstacle height significantly affected all kinetic parameters ($p < 0.001$) such that all increased with increasing obstacle height. Fast walking speed

Table 1. Kinematic gait parameters.

Parameter		Bottle				Obstacle			Speed	
		CF (A)	RD (B)	AL (C)	FG (D)	0 cm (E)	10 cm (F)	30 cm (G)	Normal (H)	Fast (J)
Overall gait speed (m/s)		1.56 (0.03)	1.55 (0.03)	1.56 (0.03)	1.53 (0.03)	1.61^{FG} (0.03)	1.56^{EG} (0.03)	1.48^{EF} (0.03)	1.29^{J} (0.02)	1.81^{H} (0.04)
Single leg support time (sec)		0.56 (0.02)	0.59 (0.02)	0.57 (0.02)	0.56 (0.02)	0.44^{FG} (0.01)	0.58^{EG} (0.02)	0.69^{EF} (0.02)	0.60^{J} (0.02)	0.54^{H} (0.02)
Horizontal clearance (cm)	HCT	19.5 (1.0)	20.2 (0.9)	19.6 (0.7)	19.8 (0.9)	NA	17.8^{G} (0.9)	21.7^{F} (0.8)	17.6^{J} (0.8)	21.9^{H} (0.9)
	HCL	28.7^{D} (0.7)	28.2 (0.7)	28.0 (0.8)	26.7^{A} (0.9)		27.2^{G} (0.7)	28.6^{F} (0.7)	24.4^{J} (0.6)	31.4^{H} (0.9)
Vertical clearance (cm)	VCT	17.7 (0.6)	18.5 (0.9)	17.4 (1.2)	17.7 (1.1)		18.2 (0.7)	17.5 (1.2)	18.3 (1.1)	17.4 (0.7)
	VCL	14.5 (0.6)	14.2 (0.6)	14.2 (0.6)	14.6 (0.7)		15.5^{G} (0.6)	13.3^{F} (0.6)	14.3 (0.5)	14.4 (0.7)

CF = carbon fibre; RD = redesigned; AL = aluminium; FG = fibreglass; HCT horizontal clearance for trailing toe; HCL = leading heel clearance; VCT = vertical clearance of trailing foot; VCL = vertical clearance of leading foot.

Note: Values represent mean (SE). A superscript letter denotes significant difference from indicated condition ($p < 0.05$).

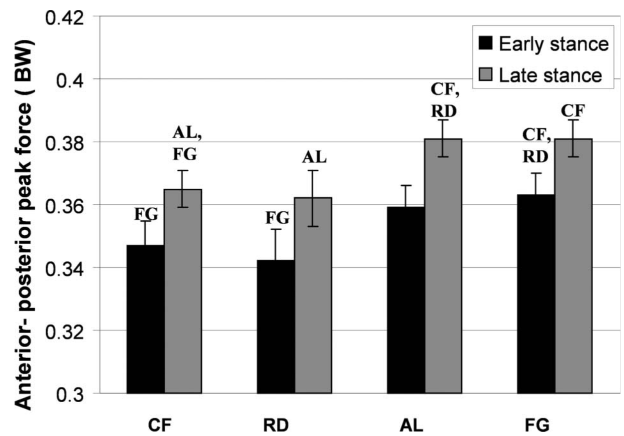

Figure 6. Anterior–posterior peak force at early and late stance. Error bars are based on pooled within cell variance. Capital letters denote significant difference from indicated bottle configuration (carbon fibre (CF), redesigned (RD), aluminium (AL) and fibreglass (FG)) ($p < 0.05$). BW = body weight.

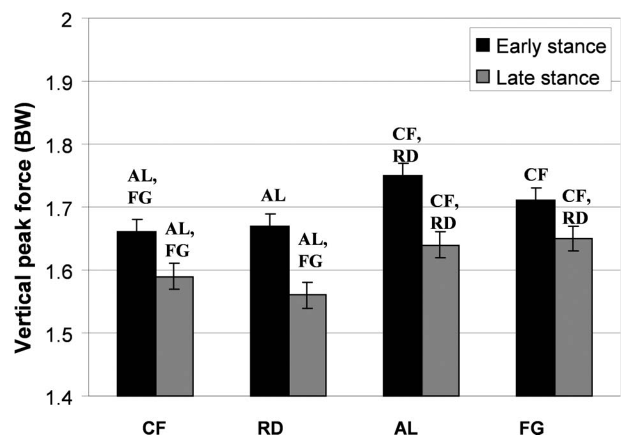

Figure 7. Vertical peak forces at early and late stance. AL = aluminium; FG = fibreglass; CF = carbon fibre; RD = redesigned; BW = body weight.

significantly led to greater anterior–posterior and vertical peak GRF ($p < 0.005$). In contrast, anterior–posterior and vertical impulse significantly decreased ($p < 0.005$) with increasing walking speed except anterior–posterior impulse at early stance.

Bottle × obstacle interaction effects were also found for anterior–posterior peak force and impulse at early stance, such that peak force and impulse increased with obstacle height and FG, followed by AL, had the greatest rate of increase. There were no significant differences in medial–lateral peak force and impulse due to bottle configuration. No significant effects on any kinetic parameters were found between the bottle conditions that had the same mass but different

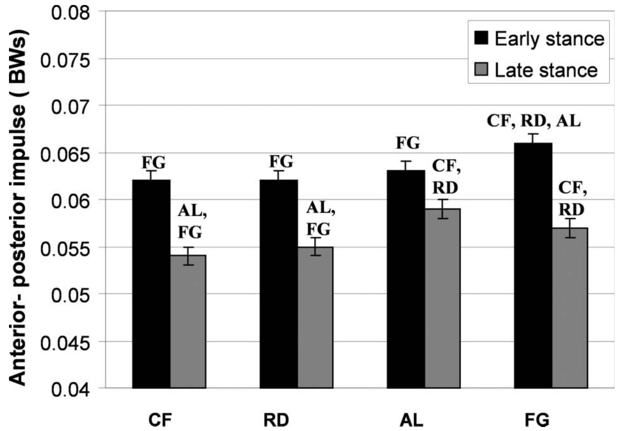

Figure 8. Anterior–posterior impulse normalised by body weight (BW) at early and late stance. FG = fibreglass; AL = aluminium; CF = carbon fibre; RD = redesigned.

configuration. No significant interaction effects between walking speed and bottle configuration were found for any kinetic parameter. Significant interactions between instructed walking speed and obstacle height were found for anterior–posterior peak force and impulse at early stance ($p \leq 0.02$).

Peak GRFs in both the anterior–posterior and vertical directions were greater for the heavier bottles (AL, FG) (Figures 6 and 7). Significant differences in early and late stance vertical peak forces were found between the lightweight bottles (CF, RD) and the heavier and larger AL bottle ($p < 0.001$). Early, late and total maximum anterior–posterior peak force increased with increasing bottle mass, speed and obstacle height ($p < 0.039$, Table 2). Late stance anterior–posterior impulses of the heavier bottles (AL, FG) were significantly greater than the lighter bottles (CF, RD) ($p < 0.001$, Figure 8).

Discussion

In this study, kinematic and kinetic gait parameters were examined to explore the effect of firefighter SCBA bottle configuration (bottle mass and size) on gait performance while walking over obstacles and at different walking speeds. It was hypothesised that reductions in mass and size of the air bottle would improve gait performance, which in turn may lead to a reduced likelihood of slips and trips and reduced fall risk. The clearest finding from this study was that gait performance of firefighters was strongly influenced by the mass of their SCBA air bottle. In particular, use of the heavier bottles (AL, FG) resulted in reduced obstacle clearance, with occasional obstacle contact, and larger vertical and anterior–posterior peak forces and impulses when compared with the lighter bottles (CF, RD).

Table 2. Kinetic gait parameters.

Parameter		Bottle				Obstacle			Speed	
		CF (A)	RD (B)	AL (C)	FG (D)	0 cm (E)	10 cm (F)	30 cm (G)	Normal (H)	Fast (J)
GRF Anterior–Posterior	Early peak	0.347^{D} (0.028)	0.342^{D} (0.02)	0.359 (0.026)	0.363^{AB} (0.028)	0.288^{FG} (0.025)	0.35^{EG} (0.023)	0.42^{EF} (0.029)	0.296^{J} (0.024)	0.409^{H} (0.027)
	Late peak	0.365^{CD} (0.026)	0.362^{C} (0.021)	0.381^{AB} (0.027)	0.381^{A} (0.028)	0.309^{FG} (0.024)	0.394^{EG} (0.026)	0.415^{EF} (0.028)	0.341^{J} (0.026)	0.403^{H} (0.025)
	Early impulse	0.062^{D} (0.005)	0.062^{D} (0.004)	0.063^{D} (0.004)	0.066^{ABC} (0.005)	0.044^{FG} (0.003)	0.061^{EG} (0.004)	0.083^{EF} (0.006)	0.062 (0.004)	0.064 (0.005)
	Late impulse	0.059^{CD} (0.004)	0.055^{CD} (0.003)	0.059^{AB} (0.004)	0.057^{AB} (0.003)	0.043^{FG} (0.003)	0.057^{EG} (0.004)	0.069^{EF} (0.004)	0.059^{J} (0.004)	0.054^{H} (0.003)
	Total peak	0.39^{CD} (0.028)	0.386^{D} (0.023)	0.404^{A} (0.031)	0.404^{AB} (0.029)	0.322^{FG} (0.026)	0.414^{EG} (0.027)	0.453^{EF} (0.031)	0.351^{J} (0.027)	0.441^{H} (0.029)
	Total impulse	0.116^{CD} (0.008)	0.117^{CD} (0.007)	0.121^{AB} (0.008)	0.123^{AB} (0.008)	0.087^{FG} (0.007)	0.119^{EG} (0.008)	0.152^{EF} (0.01)	0.121 (0.008)	0.118 (0.008)
GRF Vertical	Early peak	1.66^{CD} (0.09)	1.67^{C} (0.09)	1.75^{AB} (0.1)	1.71^{A} (0.1)	1.58^{FG} (0.08)	1.71^{EG} (0.09)	1.8^{EF} (0.1)	1.55^{J} (0.09)	1.84^{H} (0.1)
	Late peak	1.59^{CD} (0.08)	1.56^{CD} (0.06)	1.64^{AB} (0.07)	1.65^{AB} (0.08)	1.49^{FG} (0.07)	1.61^{EG} (0.06)	1.73^{EF} (0.08)	1.56^{J} (0.08)	1.66^{H} (0.07)
	Early impulse	0.38 (0.01)	0.41 (0.03)	0.4 (0.02)	0.4 (0.01)	0.36^{G} (0.02)	0.4^{G} (0.02)	0.44^{EF} (0.02)	0.43^{J} (0.02)	0.37^{H} (0.02)
	Late impulse	0.38 (0.02)	0.41 (0.03)	0.39 (0.01)	0.4 (0.02)	0.33^{G} (0.02)	0.37^{G} (0.01)	0.48^{EF} (0.02)	0.47^{J} (0.02)	0.32^{H} (0.01)
	Total peak	1.72^{CD} (0.09)	1.71^{CD} (0.09)	1.79^{AB} (0.1)	1.78^{AB} (0.09)	1.63^{FG} (0.09)	1.76^{EG} (0.09)	1.85^{EF} (0.1)	1.61^{J} (0.09)	1.89^{H} (0.1)
	Total impulse	0.76 (0.03)	0.82 (0.06)	0.79 (0.03)	0.80 (0.03)	0.70^{G} (0.04)	0.77^{G} (0.03)	0.91^{EF} (0.03)	0.89^{J} (0.04)	0.69^{H} (0.03)

CF = carbon fibre; RD = redesigned; AL = aluminium; FG = fibreglass.

Note: Values represent mean (standard error). Ground reaction force (GRF) peak and impulse values are normalised by body weight. A superscript letter denotes significant difference from indicated condition ($p < 0.05$).

Kinematic analysis

One of the most striking results was that 10 out of 24 subjects (42%) hit the taller (30 cm) obstacle with their trailing foot at least once while wearing a heavier bottle (AL, FG). None of the subjects made contact with the obstacle while carrying the lightweight bottles. In addition, a significant bottle × obstacle interaction effect for VCL ($p = 0.034$) also suggested that VCL was smallest while wearing the heavier AL bottle and crossing the 30 cm obstacle (VCL = 12.5 ± 0.8 cm). The mean VCL for the 30 cm obstacle was smaller than for the 10 cm obstacle (13.3 cm vs. 15.5 cm). Instructed walking speed (normal, fast) had no effect on vertical clearance or likelihood of contacting the obstacle. Although obstacle contact only occurred with the trailing foot, no statistical difference in VCT was found with regard to bottle configuration ($p > 0.05$); however, non-significant trends suggest that use of heavier bottles was associated with smaller clearances and greater variability in VCT (Table 1). Thus, during trials with heavier bottles, subjects may have held their trailing foot slightly lower and with less control than with lighter bottles. Another potential explanation for why VCL showed a significant interaction effect and VCT did not may be attributed to the presence of visual feedback to assist in controlling the location of the lead foot. Subjects could look at their leading limb when crossing over the obstacle, so they would be able to adjust their lead leg clearances more effectively than their trailing limb. Since they must move their trailing limb without any visual information, subjects tended to lift their trailing limb higher but with less control, such that the mean values and standard errors were greater for VCT than VCL (Table 1). These findings are important because they suggest that carrying a heavier bottle may place a firefighter at greater risk for a trip and a fall, particularly when crossing over challenging obstacles.

Kinetic analysis

Significant differences in both anterior–posterior and vertical peak forces were found between the lighter bottles (CF, RD) and the heavier bottles (AL, FG) (Figures 6 and 7, Table 2). Wearing the heavier bottles (AL, FG) resulted in a 4.8% greater anterior–posterior peak GRF at both early and late stance compared with the lighter bottles (CF, RD). Similarly, greater vertical peak GRFs were noted with the heavier bottles (AL, FG) than the lighter bottles (CF, RD). Participants wearing the heavier bottles produced an increase in vertical peak GRF by 3.9% at early stance and 4.4% at late stance. Increased walking speed also resulted in greater anterior–posterior and vertical peak forces (Table 2). Medial–lateral GRF parameters, however, were not significantly affected by bottle mass, a finding that is supported by previous studies (Kinoshita 1985, Lloyd and Cooke 2000). The present results support previous load-carriage studies reporting that vertical and anterior–posterior GRF increased proportionally with increased carrying load weight (Kinoshita 1985, Lloyd and Cooke 2000, Birrell *et al*. 2007). As a side study, kinetic parameters were also normalised by the combination of subject weight plus bottle weight. No significant differences due to bottle configuration were found for these parameters. These results support that the observed differences in peak GRF and impulse when normalised only by body weight were due to the addition of bottle mass.

The larger peak forces due to increased bottle mass could be a cause of concern for increased risk for slipping and lower limb injury. Previous studies have reported that the magnitude of anterior–posterior force at heel contact increases with higher heel contact velocity, which was considered to increase the risk of slip-induced falls (Perkins and Wilson 1983, Mills and Barrett 2001). Others have reported that a slip would initiate whenever the anterior–posterior force was greater than the frictional force (Hanson *et al*. 1999, Lockhart and Kim 2006). It was noted that, during early stance, larger anterior-directed forces were found for heavier bottles. Similarly, during late stance, larger posterior-directed forces were found. Given the wet and slippery environment of the fire ground, these larger horizontal forces could put the firefighter wearing a heavier SCBA at greater risk for either a backward slip during early stance or a forward slip during late stance. Further, excessive GRFs, especially vertically directed, are a major risk factor for musculoskeletal (overuse) injuries to the lower extremity (Cavanagh and Lafortune 1980, Birrell *et al*. 2007). Therefore, the larger peak vertical forces associated with wearing heavier bottles may also put firefighters at greater risk of lower extremity injuries.

Increase in bottle mass also resulted in larger anterior–posterior impulse at both early and late stance (Figure 8). Moreover, a significant difference between AL and FG bottles in early stance was observed. The magnitude of the impulse will be greater due to an increase in the duration of the foot contact as well as an increase in GRF. Since there was no significant difference of anterior–posterior peak force in early stance between AL and FG bottles, this difference in impulse might be due to longer time in early stance. Longer early stance time when wearing the FG bottle might be due to subjects' unfamiliarity with the FG bottle, which was artificially constructed for the current study to have the same mass as the

AL bottle. Unexpected longer time in early stance might be associated with difficulty in braking their foot. Recognising that the majority of falls occur during the heel contact phase of gait cycle (Hanson *et al.* 1999, Lockhart and Kim 2006), insufficient control of foot braking might be related to increased fall risk.

Conclusions

In conclusion, increasing load carriage weight from heavier SCBA air bottles resulted in reduced gait performance. That is, when the firefighters were wearing the heavier bottles, they exhibited a greater likelihood of contacting a tall and challenging obstacle, reduced obstacle clearance and greater forces between the trailing foot and ground while crossing an obstacle. Increasing obstacle height and walking speed also increased both anterior–posterior and vertical peak forces.

No significant differences were found in the measured gait parameters between CF and RD bottles, which have the same weight but different bottle size. These results suggest that reducing the bottle height, which lowered the location of CoM, had little effect on the gait parameters when compared with a commercially available lightweight bottle (CF). However, the shorter bottle (RD) may have an advantage when a firefighter confronts an overhanging obstacle. When a firefighter tries to avoid an overhanging obstacle by lowering the head and upper body, the shorter length of the RD bottle may make it less likely to hit an overhanging obstacle. Further study is necessary to determine if there is additional merit in developing a short and lightweight SCBA bottle.

An important implication of this study is that firefighters need to be cognisant of how their PPE may affect their gait performance, especially in challenging environments. At the same time, these results should be considered when fire departments make future PPE purchasing decisions. Carrying a heavier SCBA may increase the risk of tripping over obstacles (as shown by the increased obstacle contacts and smaller obstacle clearances) and place firefighters at greater risk for slipping on wet or icy surfaces (due to larger contact forces). This could potentially result in one of the most common and costly injuries on the fire ground.

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