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Field evaluation of a new prototype self-contained breathing apparatus

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Firefighters are required to use a self-contained breathing apparatus (SCBA) for respiratory protection when engaged in a variety of firefighting duties. While the SCBA provides crucial respiratory support and protection, it is also cumbersome and heavy, thus adding to the physical work performed by the firefighter. The purpose of the present study was to evaluate and compare the low profile SCBA prototype to a standard SCBA, as assessed by the objective and subjective measures of mobility and comfort, time of donning/doffing, as well as by acquiring user feedback on SCBA design features during field activities. The results of the present study indicated that the prototype SCBA was rated as a significant improvement over the standard SCBA in the areas of range of motion (ROM), mobility, comfort, induction of fatigue, interaction with protective clothing, and operability when worn over a standard firefighter ensemble, while performing a series of International Association of Fire Fighters Fire Ground Survival Program training exercises.

Statement of Relevance: A prototype SCBA was evaluated and compared with a standard SCBA, focusing on the objective and subjective measures of mobility and comfort during field activities. Feedback from end users was collected during the evaluation. The findings of the present study can be used for improving the system design and overall performance of new prototype SCBAs.

Keywords: self-contained breathing apparatus; range of motion; subjective perceptions; firefighters

1. Introduction

It is well known that protective clothing and personal protective equipment (PPE) can restrict wearer mobility to some extent (Huck 1988, 1991, Havenith and Heus 2004, Coca *et al.* 2008, 2010). However, when determining the performance of PPE, it is important to establish a balance between the protection provided against a myriad of hazards and the comfort and functional mobility of the PPE. Firefighters are required to use a self-contained breathing apparatus (SCBA) for respiratory protection when engaged in a variety of firefighting duties. While the SCBA provides crucial respiratory support and protection, it is also cumbersome and heavy (between 12 and 18 kg for most of the SCBAs), thus adding to the physical work performed by the firefighter (Louhevaara *et al.* 1984, Love *et al.* 1994, Hooper *et al.* 2001, Dorman 2007, Dorman and Havenith 2009). Weight of the SCBA has been identified as the factor most affecting the physiological strain of the wearer. Heavier SCBA increases heart rate, oxygen consumption, and ventilation rate (Sykes 1993, Hooper *et al.* 2001, Dorman 2007, Dorman and Havenith 2009). The SCBA also imposes limitations on the firefighter range of motion (ROM), changes the centre of gravity of the firefighter leading to the potential for loss of balance, and, finally, increases the potential for entanglement and limited movement in confined spaces. Moreover, certain design features of SCBA, such as size and harnessing, have been identified as causing difficulties in using SCBA that may negatively impact a wearer's performance and/or comfort (Love *et al.* 1994, Bakri *et al.* 2011).

Lastly, another important factor regarding PPE is user comfort. Hooper *et al.* (2001) claimed that lightweight SCBAs had a clear advantage over heavier SCBAs. However, they did not ascribe the benefit to the reduction in weight exclusively, since the design of the tested SCBAs also changed considerably. They concluded that the lightweight SCBA was more comfortable due to a combination of factors such as weight, design, and components of the SCBA. Recently, a new prototype SCBA called the low profile SCBA prototype [International Association of Fire Fighters (IAFF) and Mine Safety Appliances Company (MSA), Pittsburgh, PA] was developed in an effort to improve upon the limiting factors associated with the use of a conventional SCBA mentioned above. Thus, there was a need to assess the new prototype SCBA to determine fire service acceptability

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of a new technology for improved protection and whether design features of the prototype SCBA create further encumbrance and/or limits imposed on firefighters. The purpose of the present study was to evaluate and compare the low profile SCBA prototype to a standard SCBA, by assessing the objective and subjective measures of mobility and comfort, time of donning/doffing, as well as by acquiring user feedback on SCBA design features during field activities.

2. Methods

2.1. *Subjects*

Fifteen professional firefighters (12 males and 3 females) between the ages of 20 and 45 years agreed to participate in this study. The subjects' demographic characteristics are 12 males (mean $\pm$ SD): age 35.9 $\pm$ 8.3 years; height: 173.5 $\pm$ 19.8 cm; body mass: 89 $\pm$ 11.4 kg; and 3 females: age 35 $\pm$ 7.9 years; height: 169.7 $\pm$ 6.3 cm; body mass: 65 $\pm$ 5.6 kg. The study reflects the fact that there are fewer females than males in the US fire service. Clearance to perform the field evaluation was obtained from the National Institute of Occupational Safety and Health (NIOSH) Human Subject Review Board, and both oral and written informed consents were obtained from each subject prior to his/her participation.

2.2. *Experimental procedures*

2.2.1. *Experimental SCBA*

In an effort to improve on the standard SCBA, the U.S. Department of Homeland Security funded the IAFF to develop a next generation SCBA that incorporated new materials and technology aimed at developing a lighter weight and lower profile SCBA compared with a standard SCBA, while providing a comparable volume of air (1800 l or 45 rated min) to the user. MSA (Pittsburgh, PA) was selected by the IAFF and its established User Technical Advisory Committee to manufacture the prototype SCBA known as the low profile SCBA (Figure 1) according to the requirements and guidelines of the IAFF. The prototype consists of an assembly of five compressed-air pressure vessels constructed using a special plastic lining in place of conventional aluminium liners used in current SCBA cylinders. These blow moulded linings are covered with braided Kevlar and wound with pre-impregnated carbon fibre. The entire assembly is secured inside a soft, flexible cover, allowing the design to flex horizontally and vertically at the connection points. The pressure vessel array is designed to be pressurised to 4500 psi, and it supplies the same volume of air as a conventional 45-min rated

Figure 1. The low profile prototype SCBA.

SCBA. However, the pressure vessels of the prototype SCBA were not filled with air during this field evaluation, since the safety certification approval by the Department of Transportation (DOT), required to conduct the exercise with filled pressure vessels, was still in the final review phase. The fact that the pressure vessels of the prototype SCBA were not filled with air did not seem to change the flexibility of the units according to the manufacturer. The conventional SCBA units used for this study were not filled with air to allow comparison with the prototype SCBA. Due to the new size and design, the harnessing and straps also differ from the standard SCBA. The prototype low profile SCBA is constructed to the following size specifications: 76 $\times$ 33 $\times$ 10 ($H \times W \times D$; cm); and it weighs 12.69 kg (SCBA + regulator + facemask). The standard SCBA used in this field study is National Fire Protection Association (1981, 2007) compliant with the following size specifications: 60 $\times$ 25 $\times$ 20 ($H \times W \times D$; cm); and it weighs 13.66 kg (SCBA + regulator + facemask). Subjects used the facemask they used with their SCBA or the one provided by MSA to fit the low profile SCBA.

Figure 2 illustrates the low profile SCBA and the standard SCBA as it is normally worn by a firefighter (centre firefighter wears a low profile prototype SCBA).

2.2.2. *Experimental protocol and procedure*

The present study was performed at the Prince George's County Fire/EMS Academy in Maryland with IAFF supporting the evaluation with technical assistance and field exercise coordination. The experimental protocol consisted of an ergonomic feature evaluation and five field exercises at separate training stations, designed to simulate activities that

Figure 2. Carrying appearance of the standard and prototype SCBA.

Figure 3. A subject performing the window egress exercise (Station 3).

firefighters encounter on duty. These activities are based on the IAFF Fire Ground Survival (FGS) Program, as described below.

Station 1 – Ergonomic feature evaluation involved timed donning/doffing an SCBA, subjective measurements on donning/doffing ease, and static/dynamic ROM.
Station 2 – Reduced profile exercise involved participation in the reduced profile exercise utilising ancillary equipment. The firefighters used FGS techniques to manoeuvre through narrow openings simulating interior stud walls.
Station 3 – Window egress exercise involved participation in a window egress exercise in which firefighters climbed a ladder to enter a second floor window and conducted a left-hand search. At a designated point, the firefighter was instructed to exit through the same window utilising the FGS low profile technique (Figure 3).
Station 4 – Entanglement exercise involved participation in the entanglement exercise utilising ancillary equipment designed and built for the IAFF FGS Program. Firefighters used FGS techniques to manoeuvre through a series of entanglement hazards simulating common electrical wiring using the following equipment: Flat Head Axe, Halligan Bar, FGS Entanglement Prop, and FGS entanglement technique.
Station 5 – SCBA confidence course involved participation in the FGS SCBA confidence course in which firefighters followed a hose line through a maze in darkness which involved various changes in direction and confined spaces.
Station 6 – Roof venting exercise involved participation in a roof venting exercise in which the participants utilised a ground level roof prop. While not an exercise in the FGS, firefighters routinely wear SCBA during roof operations. The firefighters used a ventilation saw to cut through sheets of replaceable plywood. The equipment used was a ventilation chain saw, 6′ pike pole, and a Pick Head Axe (Figure 4).

Figure 4. A subject performing the roof venting exercise (Station 6).

During participation in the experimental phase, the subjects wore a standard structural firefighter protective ensemble, which consists of the helmet, hood, turnout coat, pants, gloves, and boots. All other equipment necessary to perform a specific FGS drill was provided at each station. All subjects completed the experimental protocol twice at each station, once while wearing the standard SCBA and once while wearing the prototype SCBA. The order of the SCBA trial between the standard and prototype was randomly assigned, and a minimum 15-min rest period was afforded the subjects between the both trials at each station.

2.2.3. Measurements

2.2.3.1. Ergonomics. Ergonomic measurements included both static and dynamic ROM using a previously described ergonomics measurement protocol (Johnson 2005, Coca *et al.* 2008) as outlined below. Briefly, static ROM were measured for shoulder flexion/abduction, cervical rotation/flexion/extension, trunk flexion/extension/lateral flexion, stand and reach, overhead reach using a goniometer, torso bend device (Acuflex I, Novel Products, Inc., Rockton, IL), multi-coloured tape (for marking purposes), and tape measure. For example, measurement of cervical flexion and extension was done as follows:

- *Start position*: The subject is standing. The head and neck in anatomical position confirmed by a researcher.
- *End position*: Subject remains standing; subject's neck is flexed or extended to the limit of motion.
- *Goniometer position*: The strap is placed around the head at the mid-forehead level with the dial placed on the lateral aspect of the head.

Measurements of donning/doffing time of the standard and prototype were made using a digital timing system (Station 1). Prior to the test, MSA personnel explained the differences between both SCBAs and also explained that the low profile SCBA was donned similarly to the standard SCBA. Subjects wearing their full firefighter gear stood by a table where either the prototype or the standard SCBA was prepared to be donned. Time started when subjects approached the table to don the SCBA and was stopped when the subjects completed donning the gloves after completing harness adjustments and connecting the SCBA regulator to the full-face mask. The doffing procedure was the reverse of the donning and the time ended when the SCBA was removed and left on the table. Other measures such as 'stand and reach' and 'overhead reach' were obtained as the difference between reaching from a point in a neutral position as far as subjects could go without moving the trunk or feet. All static and dynamic activities were clearly explained to the subjects and demonstrated by experienced laboratory staff before a measurement was taken. All measurements were repeated three times by the same researcher, and an average value was reported for each subject measurement category.

Additionally, subjective ratings on donning/doffing ease were measured using a Visual Analogue Scale (VAS) consisting of a 25-cm line anchored 'None' and 'Maximal' at the two extremes (wordings of the two anchored indications were modified specific to measurement questions in the field exercise measurements). The subjective values measured were then converted to a numeric scale from 0 (None) to 100 (Maximal) by overlaying a transparent scoring sheet onto the given scales.

2.2.3.2. Field exercises. After performing each of the exercises at Stations 2–6, the subjects were given a 'set of measurements' booklet to be completed as instructed. The measurements consisted of subjective ratings using VAS on fatigue, comfort, and mobility (overall, upper, lower body, arm/shoulder) and five additional factors as follows: (1) (VAS) stability and security of (standard/prototype) SCBA components, fastenings, and adjustments; (2) (VAS) interaction and operation ease of (standard/prototype) SCBA and its components with the ensemble (e.g. helmet and turnout gear); (3) the suitability of (standard/prototype) SCBA to your job-related tasks (0: poor–10: optimal); (4) identify any factors of (standard/prototype) SCBA that reduced mobility, fit, or comfort during activity you just performed; and (5) identify any perceived restrictions and/or functional limitation of (standard/prototype) SCBA on carrying out actions during activity you just performed.

2.3. Statistical analysis

All data were first calculated and presented as mean and standard deviation for each measurement category across the standard and prototype SCBA trials. Then, the data were paired for each individual and changes in the measurements were calculated as percentages from the standard to prototype SCBA trials. Paired data in static, dynamic ROM, and subjective measures were analysed by paired-samples t test to determine the groups' mean difference using a statistical software package (SPSS v.18.0). Unpaired subjects' data were excluded from statistical analysis, and the subjects' feedback and/or comments for open answer questions 4–5 were presented as categorical data without statistical analysis. Alpha level was set at 0.05.

3. Results

3.1. Ergonomic feature evaluations in Station 1

The results of ergonomic feature evaluations performed at Station 1 are summarised in Table 1. There was no significant difference in the donning/doffing times when comparing the standard versus the prototype SCBA. In parallel with this result, there was also no statistical difference detected in subjective ratings on donning/doffing ease. In measurements of static ROM, it was revealed that shoulder flexion and trunk extension were greater (gain; $p < 0.05$) for the

Table 1. Summary of ROM measurements.

	Standard SCBA	Prototype SCBA	% change[a]	p value	n[b]
Donning time (s)	48.7 (12.0)	45.7 (11.1)	−6.2	0.247	15
Donning ease[c]	66.7 (20.8)	74.6 (13.5)	11.8	0.242	15
Doffing time (s)	21.3 (5.4)	20.7 (5.1)	−2.9	0.370	15
Doffing ease[c]	72.3 (19.3)	80.6 (16.8)	11.4	0.140	15
Shoulder flexion (°)	135.9 (13.7)	140.9 (12.8)	3.7	0.037	15
Shoulder abduction (°)	124.8 (6.8)	140.9 (27.8)	12.9	0.055	15
Cervical rotation (°)	52.2 (9.4)	54.8 (5.7)	5.0	0.296	15
Cervical flexion (°)	46.2 (7.1)	44.5 (9.9)	−3.8	0.335	15
Cervical extension (°)	43.1 (10.3)	48.8 (11.7)	13.2	0.075	15
Trunk flexion (°)	111.3 (11.6)	103.6 (23.9)	−6.9	0.262	15
Trunk extension (°)	41.2 (7.4)	47.4 (9.2)	15.2	0.038	15
Trunk lateral flexion (°)	51.5 (12.4)	46.3 (7.5)	−10.0	0.084	15
Stand/reach (cm)	30.6 (7.6)	31.0 (6.6)	1.5	0.737	15
Overhead reach (cm)	13.0 (3.0)	15.3 (8.3)	17.6	0.174	15

Note: Values are mean (SD). [a]Calculated as per cent changes in the measurements from standard to prototype SCBA. [b]Number of subjects included in statistical analysis (a paired t test). [c]Subjective measurements using VAS (0–100).

prototype than standard SCBA. However, there was no difference in any cervical or reach measurements. Regardless of statistical significance, cervical flexion, trunk flexion, and lateral flexion were the only factors measured showing loss of static ROM in the prototype compared with the standard SCBA.

3.2. *Field evaluations in Stations 2–6*

The results for subjective ratings on comfort, mobility, and fatigue during field evaluations at Stations 2–6 are summarised in Table 2. In the subjective measures following the five different field exercises, most of the measurement factors showed statistically significant differences between the standard and prototype SCBA. The results showed that the subjects significantly perceived higher comfort, greater mobility, and less fatigue when they performed the assigned exercises with the prototype as opposed to the standard SCBA, except for the following factors: lower body comfort and mobility in reduce profile and SCBA confidence exercises; and fatigue in reduce profile and entanglement exercises.

Regarding subjective measures on stability, interaction, and suitability of SCBA, subjects rated the prototype SCBA more stable and secure in its components across all the exercises, but significance was attained only in the roof venting exercise (Figure 5). Subjects also rated the interaction and operation of the prototype SCBA and its components with the firefighter ensemble they wore as significantly improved compared with the standard SCBA across all the exercises except in reduce profile exercise (Figure 6). The results also showed that the subjects rated the prototype SCBA significantly more suitable for the overall job-related tasks of firefighters as determined from the overall performance of the present set of field exercises they performed in Stations 2–6 (Figure 7).

Additionally, the subjects provided their comments regarding two specific questions used to determine the limiting factors to performance and comfort of both the standard and prototype SCBA. Figure 8 shows a summary of subjects' comments to the question: 'identify any factors of (standard/prototype) SCBA that reduce mobility, fit, or comfort during the activity you just performed'. Weight and size were most frequently identified for the standard SCBA to reduce the subjects' mobility, fit, or comfort while security/design of backpack straps and length of backpack were identified for the prototype SCBA. In the 'other' category for the standard SCBA, factors such as 'overhead restriction', 'helmet interaction', or 'limited reach during left-hand search' were made. For the prototype, factors such as 'had to find right adjustment due to lightweight feeling' or 'square shape of upper corners' were pointed out. Figure 9 shows a summary of subjects' comments to the question: 'identify any perceived restrictions and/or functional limitation of (standard/prototype) SCBA on carrying out actions during the activity you just performed'. For the standard SCBA, SCBA design in overall and weight-related factors were most often identified to negatively affect their performance, while no subjects identified weight as a factor in the prototype SCBA. Rather, most comments about the prototype were specific design features such as width and length of backpack and cylinder valve position. In the 'other' category for the standard SCBA, factors such as 'manipulation of straps for cylinder removal challenging', 'keeping cylinder in corner', or 'unable to move freely when changing direction' were made. For the prototype,

Table 2. Summary of subjective measurements on comfort, mobility, and fatigue.

	Measurements	Standard SCBA	Prototype SCBA	% change[a]	*p* value	*n*[b]
Reduce profile	Overall body comfort	49.5 (21.0)	80.4 (12.3)	62.2	0.001	11
	Overall body mobility	44.9 (17.9)	74.0 (20.5)	64.8	0.007	11
	Upper body comfort	42.3 (19.0)	77.9 (13.4)	84.3	0.001	11
	Upper body mobility	44.5 (20.6)	74.4 (22.5)	66.9	0.019	11
	Lower body comfort	60.4 (25.9)	79.5 (13.6)	31.6	0.085	10
	Lower body mobility	60.8 (25.7)	78.0 (19.3)	28.3	0.119	10
	Arm/shoulder comfort	46.8 (20.1)	79.1 (15.8)	68.9	0.003	11
	Arm/shoulder mobility	46.9 (21.1)	78.5 (21.3)	67.2	0.014	11
	Fatigue	45.6 (19.7)	31.5 (23.8)	−30.9	0.087	11
Window egress	Overall body comfort	56.3 (21.9)	79.9 (14.7)	41.9	0.001	15
	Overall body mobility	57.1 (19.9)	80.5 (15.2)	40.8	0.001	15
	Upper body comfort	49.7 (17.5)	78.9 (14.5)	58.9	<0.001	15
	Upper body mobility	50.0 (17.0)	79.8 (14.2)	59.6	<0.001	15
	Lower body comfort	61.8 (20.7)	77.5 (17.1)	25.4	0.012	15
	Lower body mobility	63.0 (20.1)	75.3 (17.9)	19.6	0.039	15
	Arm/shoulder comfort	51.1 (20.0)	79.0 (16.8)	54.5	0.001	15
	Arm/shoulder mobility	48.1 (19.7)	79.1 (17.0)	64.6	<0.001	15
	Fatigue	39.5 (13.4)	26.6 (20.3)	−32.7	0.015	15
Entanglement	Overall body comfort	49.3 (21.5)	81.6 (12.3)	65.4	<0.001	15
	Overall body mobility	46.2 (22.4)	80.1 (14.1)	73.4	<0.001	15
	Upper body comfort	48.0 (22.0)	82.0 (10.8)	70.8	<0.001	14
	Upper body mobility	47.7 (22.1)	79.7 (12.8)	67.1	<0.001	14
	Lower body comfort	62.4 (18.6)	82.4 (14.4)	32.2	0.007	14
	Lower body mobility	60.1 (17.7)	76.8 (16.5)	27.8	0.015	14
	Arm/shoulder comfort	46.9 (22.0)	82.0 (11.8)	75.0	<0.001	15
	Arm/shoulder mobility	44.9 (23.8)	80.5 (13.1)	79.2	<0.001	15
	Fatigue	36.7 (22.1)	31.1 (29.5)	−15.4	0.375	15
SCBA confidence	Overall body comfort	47.9 (24.0)	75.6 (14.3)	57.8	0.002	13
	Overall body mobility	41.2 (20.9)	76.2 (15.4)	85.2	<0.001	13
	Upper body comfort	43.5 (21.9)	75.7 (16.0)	74.2	0.001	13
	Upper body mobility	39.3 (22.3)	75.8 (17.0)	93.0	<0.001	13
	Lower body comfort	60.2 (26.5)	69.4 (22.0)	15.3	0.137	13
	Lower body mobility	59.5 (17.2)	68.5 (22.1)	15.3	0.169	13
	Arm/shoulder comfort	39.4 (22.3)	76.1 (17.2)	93.2	<0.001	13
	Arm/shoulder mobility	38.4 (21.0)	76.2 (17.2)	98.6	<0.001	13
	Fatigue	46.1 (17.0)	34.6 (17.0)	−24.9	0.046	13
Roof venting	Overall body comfort	51.4 (14.6)	82.7 (9.3)	60.8	<0.001	15
	Overall body mobility	49.9 (17.8)	83.0 (10.8)	66.2	<0.001	15
	Upper body comfort	49.3 (17.2)	80.2 (13.6)	62.8	<0.001	15
	Upper body mobility	47.9 (17.7)	81.1 (12.7)	69.4	<0.001	15
	Lower body comfort	57.1 (16.5)	73.9 (19.8)	29.4	<0.001	15
	Lower body mobility	59.4 (16.0)	73.7 (19.3)	24.1	0.020	15
	Arm/shoulder comfort	47.4 (17.3)	80.1 (14.4)	69.0	<0.001	14
	Arm/shoulder mobility	46.7 (19.7)	79.8 (13.4)	70.8	<0.001	14
	Fatigue	41.3 (18.1)	28.1 (22.4)	−31.8	0.035	15

Notes: Values are mean (SD). [a]Calculated as per cent changes in the measurements from standard to prototype SCBA. [b]Number of subjects included in statistical analysis: paired-samples *t* test.

factors such as '90° corners caught on wall studs' or 'hangs lower under your back' were pointed out.

4. Discussion

The main goal in the development of the low profile SCBA prototype was to improve the safety of SCBA users by modifying the design, size, and weight. This was accomplished through the application of innovative technology in the SCBA construction, which in turn improves users' comfort and mobility. Thus, the present field evaluation was designed to test the prototype SCBA by comparing it with a conventional standard SCBA with respect to ergonomics and user acceptability during the performance of firefighter activities.

4.1. Ergonomic features of the standard and prototype SCBA

The literature has suggested (Abeysekera and Shahnavaz 1987, Guidotti and Clough 1992, Stull

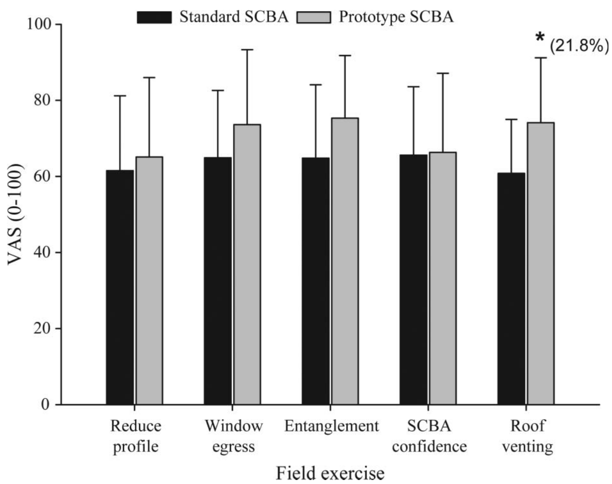

Figure 5. Stability and security of (standard/prototype) SCBA components, fastenings, and adjustments. Notes: *Statistical difference at $p < 0.05$. Value in parentheses represents per cent changes in the measurements from standard to prototype SCBA.

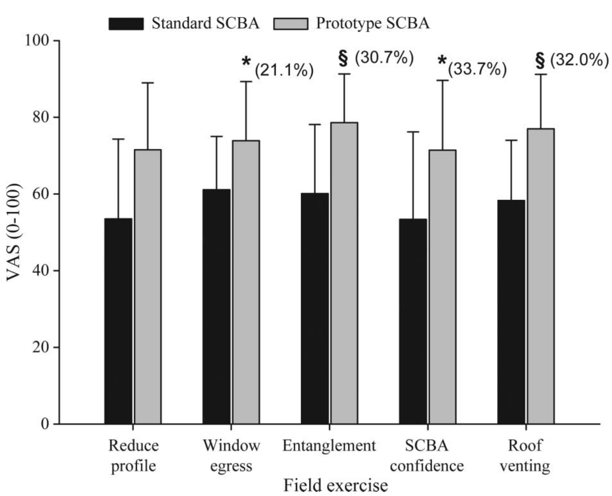

Figure 6. Interaction and operation ease of (standard/prototype) SCBA and its components with the ensemble (e.g. helmet and turnout gear). Notes: *Statistical difference at $p < 0.05$. §Statistical difference at $p < 0.01$. Value in parentheses represents per cent changes in the measurements from standard to prototype SCBA.

2000, Havenith and Heus 2004, Barker 2005, Coca *et al.* 2008, 2010) that there is a need to assess ergonomics, design features and user acceptability of any PPE system or components to better understand the suitability of the PPE evaluated. Thus, part of this field study consisted of ROM measurements to ascertain any differences between the two evaluated SCBAs. At the onset of the study, it was expected that the new size and design configuration of the prototype

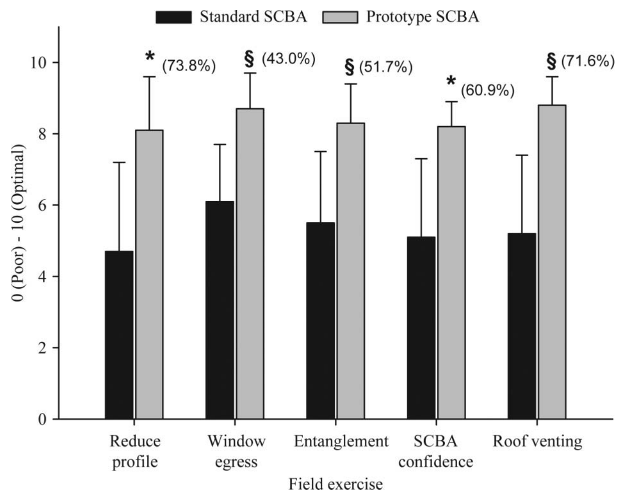

Figure 7. The suitability of (standard/prototype) SCBA to your job-related tasks (0: poor–10: optimal). Notes: *Statistical difference at $p < 0.05$. §Statistical difference at $p < 0.01$. Value in parentheses represents per cent changes in the measurements from standard to prototype SCBA.

SCBA would not significantly affect users' functional mobility. However, in the measurements of static ROM, the subjects showed significant gains in shoulder flexion and trunk extension with the prototype compared with the standard SCBA. The shoulder flexion gain could be due to more weight distributed on the back, close to the proximal part, and less pressure on shoulder straps with the new design. The gain in the trunk extension could be for similar reasons. The more even distribution of the weight and the proximity of the whole prototype SCBA on the back made the subjects feel more comfortable when extending the trunk, without the outward pull of the weight as occurs with the standard SCBA because of its configuration. For these reasons, we also anticipated significant improvement in other categories of static ROM, such as shoulder abduction and cervical extension where ROM directly and/or indirectly involves shoulder joints and the neck area. However, greater gains in such measurements failed to reach statistical significance. There was no difference in elapsed time measured for donning and doffing and also for subjective measures between the two SCBAs. This occurred despite the fact that the straps and harness design and locations on the prototype differ from those on the standard SCBA, and also the fact that the subjects did not have any training or exposure to the prototype SCBA prior to the field test, other than a brief explanation by MSA personnel regarding the differences between both SCBAs. These findings support the idea that the prototype SCBA with the new size and design at a minimum does not restrict objectively measured mobility. Thus, taken together, the data suggest that the prototype SCBA imposed less stress in terms of static and dynamic ROM than the standard SCBA.

4.2. *Subjective ratings on comfort, mobility, and fatigue*

Overall, the results showed that the subjects rated the prototype as more comfortable and that it provided better mobility compared with a standard SCBA while performing the field exercises. Specifically, ratings of comfort and mobility for overall body, upper body, and arm/shoulder appeared, by unanimous agreement, to be significantly greater in the prototype SCBA across all exercises performed, with 40–90% improvement over the standard SCBA. These results indicate that the new design features of the prototype may be advantageous, at least in terms of user comfort and mobility while wearing a whole body PPE ensemble and performing various types of field activities. However, there are difficulties in identifying exactly which features of the prototype played the most significant role in improving the subjective ratings, as Hooper *et al.* (2001) previously pointed out; it is difficult to determine which factor caused greater impact on the subjective ratings without a more in-depth analysis. Based on the factors identified by the

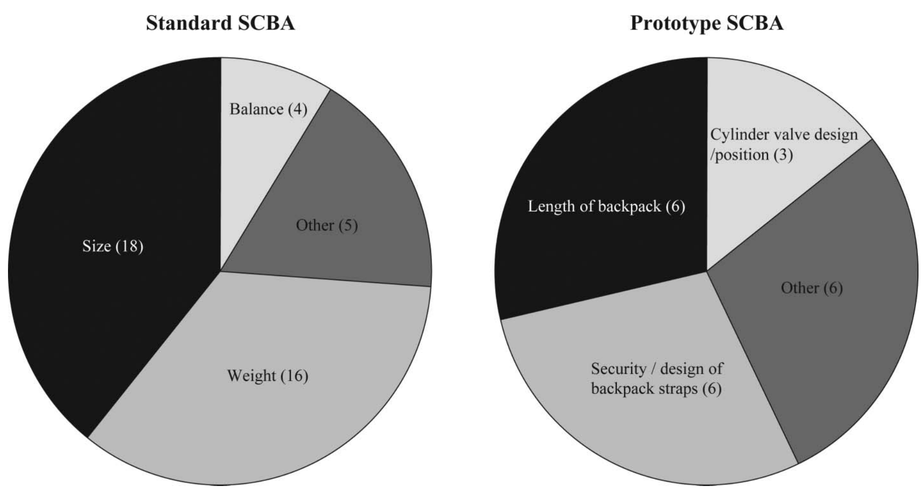

Figure 8. Summary of the subjects' comments on the question: Identify any factors of (standard/prototype) SCBA that reduced mobility, fit, or comfort during activity you just performed. Note: Total number of the comments received from the subjects: standard SCBA (43) and prototype SCBA (21).

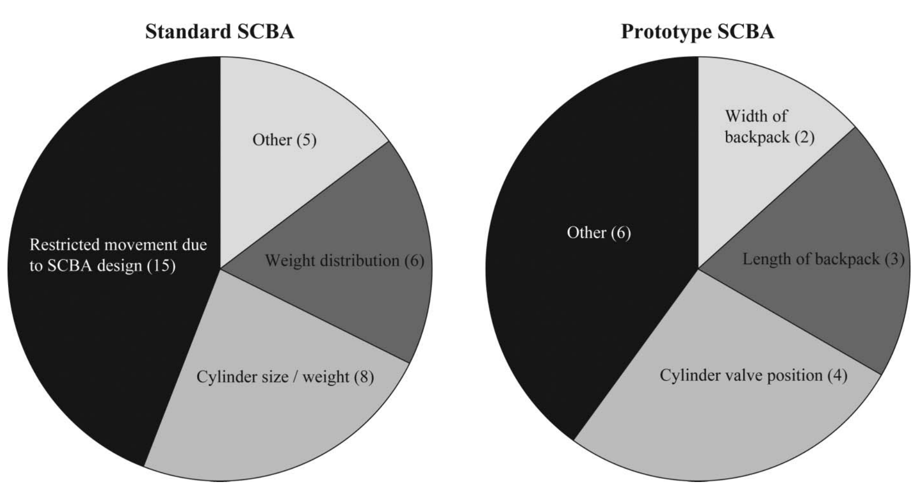

Figure 9. Summary of the subjects' comments on the question: Identify any perceived restrictions and/or functional limitation of (standard/prototype) SCBA on carrying out actions during activity you just performed. Note: Total number of the comments received from the subjects: standard SCBA (34) and prototype SCBA (15).

subjects to influence their mobility, fit, or comfort (Figure 8), good weight distribution combined with an improved centre of gravity, the back-mounting frame, and possibly the straps in the prototype seem to be the most influential factors improving the subjective ratings compared with the standard SCBA. It has been already established that there is about a 2.7% increase in energy cost per kg of clothing (Dorman 2007). Dorman also calculated about a 1% increase in energy cost with weight carried around the trunk versus weight carried in the extremities, which increases energy cost by 2.5%. Dorman's studies suggest that our subjects felt that less work was required to perform their various tasks while using the prototype SCBA for two main reasons: (1) improved distribution of weight (manufacturer claims that centre of gravity improves 35% to the standard SCBA) and (2) the 1-kg difference in weight. Pertaining to the size of the standard SCBA, the subjects pointed out that the size of the cylinder and bulkiness (dimension) of the SCBA rather than a whole system were the most problematic. Moreover, no subjects specifically identified weight or size as a limiting factor for the prototype. There were also several design features frequently identified to influence their mobility, comfort, or fit such as length of back or security/design of backpack straps (Figure 8).

4.3. *Subjective ratings on stability, interaction, and suitability of SCBA*

It has been well documented that wearing a PPE ensemble with SCBA reduces the wearers' static and dynamic ROM (Coca *et al.* 2008, 2010), impairs postural balance of the body (Punakallio *et al.* 2005), and negatively affects physical performance in both functional and muscular capacity (Louhevaara *et al.* 1984) that may increase a secondary hazard such as falls and slips (Heineman *et al.* 1989). Thus, the stability and interaction of a SCBA with PPE are of great importance in evaluating the operational feasibility of the prototype. The study results showed that subjects felt that the prototype was more stable and interacted significantly better with the ensemble while the field activities were performed. Features, identified by the subjects, of the standard SCBA that compromised stability and interaction with the ensemble were design configuration, size/weight, and weight distribution (Figure 9). These findings are very similar to those of the study by Love *et al.* (1994), who reported that about 25% of responders to a questionnaire evaluating problems associated with SCBAs indicated issues with design, weight, and size. For the prototype, certain design features (i.e. SCBA width and length) were identified as negative factors, mostly during reduce profile and window egress exercises, and cylinder valve position during the entanglement exercise; however, no subject indicated difficulties experienced for balancing his/her body or weight distribution. Finally, as shown in Figure 7, all the subjects rated the prototype as having a significantly greater suitability to their job-related tasks during the field exercises they performed. Regardless of type of exercise, overall rated scores in the suitability measurements were 5.3 (2.1) and 8.5 (1.3) out of the scale (poor: 0–optimal: 10) for the standard and prototype SCBA, respectively. A limitation to the present study is that it did not include any scientific measurements and/or examination of gauge, regulator, face piece, or air-pressure vessels of the prototype SCBA due to the DOT approval requirements.

5. Conclusions

The present field evaluation of the standard and prototype SCBAs indicated that the prototype SCBA was rated as a significant improvement over the standard SCBA in the areas of ROM, mobility, comfort, induction of fatigue, interaction with PPE, and operability when worn over a standard firefighter protective ensemble, and performing a series of FGS exercises. However, as presented previously, some of the subjects' comments were not positive and indicated several limiting factors of the prototype. These useful critiques will be used by the IAFF team to improve design and/or functional features of the prototype SCBA and eventually provide the next generation of SCBA for use in the fire service, law enforcement, and other sectors that use SCBAs.

Ultimately, the ergonomic and subjective data acquired during the field testing proved to be of great value for comparisons between the standard and prototype SCBA. It is important to point out that the prototype tested was in mid-stage development and will continue to evolve throughout the life of the project. Feedback from this field test positively supported changes to the prototype. The ergonomics test protocol reported in this evaluation is part of a full ergonomic test protocol used for the evaluation of PPE. Further refinements of the protocol would be expected as experience with this test protocol expands. Incorporation of a standard test protocol for the ergonomic feature evaluation of PPE may result in the implementation of improvements in PPE that will enhance mobility and function during use. Future evaluations of this prototype SCBA should include important issues such as maintenance, ease of servicing, and/or cylinder changes.

Disclaimer

The findings and conclusions of this manuscript are those of the authors and do not necessarily reflect the views of the National Institute for Occupational Safety and Health. Mention of any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

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