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ORIGINAL ARTICLE

Ergonomic comparison of a chem/bio prototype firefighter ensemble and a standard ensemble

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Abstract Firefighter turnout gear and equipment protect the wearer against external hazards but, unfortunately, restrict mobility. The aim of this study was to determine the ease of mobility and comfort while wearing a new prototype firefighter ensemble (PE) with additional chemical/biological hazard protection compared to a standard ensemble (SE) by measuring static and dynamic range of motion (ROM), job-related tasks, and comfort. Eight healthy adults (five males, three females), aged 20–40 years, participated in this study. The study consisted of two repeated phases, separated by five uses of the ensembles. Subjects randomly donned either the SE or PE in either dry or wet conditions on separate days. In each phase, five tests were carried out as follows: baseline (non-ensemble), SE-dry, SE-wet, PE-dry, and PE-wet. There was a significant reduction ($P < 0.05$) of wrist flexion for PE-dry condition compared to the same SE-dry condition. Donning the PE took 80 s longer than the SE in phase 1, this difference disappeared in phase 2. There was a significant decrease ($P < 0.05$) in post-test comfort wearing the PE compared to the SE. The data collected in this study suggest that, in spite of design features to enhance chemical/biological hazard protection, the PE design does not decrease the wearer's overall functional mobility compared to the SE. However, subjects seem to be more comfortable wearing the SE compared to the PE. These overall findings support the need for a comprehensive ergonomic evaluation of protective clothing systems to ascertain human factors issues.

Keywords Protective equipment · Ergonomics · Firefighters · Comfort

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Introduction

Firefighting is one of the most physically demanding occupations, requiring personnel to perform numerous activities with minimal restriction of movement. The elevated threat of terrorist attacks within the United States has created a sense of urgency for improving the protection of first responders, especially firefighters, against chemical, biological, and radiological hazards without increasing their physiological "burden". To address these hazards the National Fire Protection Association (NFPA) recently released its NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting (National Fire Protection Association 2007). This new edition to NFPA 1971 includes optional requirements for structural fire fighting protective ensembles that will provide limited protection from specific chemical warfare agents, toxic industrial chemicals, biological agents and radiological particulates (CBRN) terrorism hazards. The prototype firefighting ensemble (PE) evaluated during this ergonomic comparison was developed to comply with the optional CBRN hazard protection requirements in NFPA

1971 (National Fire Protection Association 2007). Significant advances have been made in the field of chemical protective clothing. However, the lack of attention to ergonomics and human factors issues in clothing design remains a challenge and needs to be assessed (Guidotti and Clough 1992; Barker 2005; Stull 2000). ASTM F 1154 (American Society for Testing and Materials 2004) is an example of an available standardized test for qualitatively evaluating the comfort, fit, function, and integrity of chemical protective ensembles. Nevertheless, these protocols need to be adapted to suit different protective ensembles and functionalities (Barker 2005).

Firefighter turnout gear and equipment protect the wearer against external hazards, but may adversely affect the range of motion, mobility, and comfort. Several studies have demonstrated that wearer mobility and comfort are affected by variations in garment design, sizing, and fit (Havenith and Heus 2004; Huck 1988, 1991). Furthermore, improper fit and/or poor design of ensembles may restrict the movement of the wearer.

The evaluation of motion and mobility imposed by the fire fighters' ensembles as well as the performance evaluation of the materials is of primary importance. It is also important to quantify the contribution of the turnout gear to comfort. Comfort is identified by several factors such as feel, fit, and function (Goldman 2005). Wearers can perceive differences between ensembles based on feelings of heat and skin wetness that determine their comfort level wearing the outfit (Barker et al. 2000; Stull and Duffy 2000). Comfort and mobility are important issues related to user acceptance and safety and thus must be considered in the overall evaluation of an ensemble (Szczecinska and Lezak 2000).

This study compares a new PE with additional chemical/biological hazard protection to a standard ensemble (SE). The firefighter "standard" turnout gear (a.k.a. bunker gear) used in this investigation includes the coat, pants, boots, gloves, hood, and helmet. It meets the NFPA 1971 (National Fire Protection Association 2007) Structural clothing certification requirements. The standard firefighter ensemble served as the platform for the development of the prototype. This comparison is important since fire service acceptability of new ensemble technology for improved protection is partly dependent on not creating further encumbrance of the firefighter. It was hypothesized that there would be no significant differences between the ergonomic characteristics of the prototype as compared to the standard ensemble.

To test this hypothesis, we evaluated the objective and subjective measures of mobility and comfort of volunteer subjects while wearing a new prototype firefighter ensemble compared to a standard ensemble. This was accomplished by evaluating the static and dynamic range of motion (ROM), ergonomic assessments of job-related tasks, and perception of comfort.

Methods

Subjects

Eight healthy adults (five males, three females) between the ages of 20–40 years (three of the subjects were firefighters), who passed a screening physical examination and completed a graded exercise test to maximal $\dot{V}O_2$, participated in this study. Five males, age (mean, SD): 27 ± 6.44 years old; height: 177.5 ± 8.11 cm; body mass: 83.03 ± 12.23 kg; body surface area: 2.01 ± 0.18 m^2; body fat composition: 16.32 ± 2.29%; and three females, age 26.7 ± 6.11 years old; height: 169.3 ± 10.97 cm, body mass: 64.33 ± 10.26 kg, body surface area: 1.75 ± 0.18 m^2; body fat composition: 18.67 ± 4.14% comprised the study participants. Body fat composition was measured using three body site skinfolds. Subjects were all physically active in leisure activities and were not taking any medications except for birth control pills for females. The research was approved by the NIOSH Human Subjects Review Board, and both oral and written consent was obtained from all subjects prior to their participation in this study.

Experimental ensembles

Both the "standard" and "prototype" firefighter ensemble were manufactured by Morning Pride/Total Fire Group, Dayton, OH, USA. The firefighter "standard" turnout gear used in this investigation included the coat, pants, boots, gloves, hood, and helmet. The prototype ensemble used in this investigation included the coat with integrated hood, pants, modified boots, modified gloves, and helmet. The prototype coat uses the standard design mentioned above, but with the added features of a vapor penetration–resistant front zipper closure, integrated hood with face piece gasket, SCBA air exhaust system, and sleeve-glove interfaces (Fig. 1). The prototype pants are also derived from the standard ensemble above, but with the added feature a flyless front with gusset opening and boot–sock extensions. The prototype gloves are constructed of a multilayer composite with a leather shell, Crosstech® insert moisture barrier, and modacrylic thermal barrier with modified magnetic gauntlet interface. The hood is constructed of the same material as the garment and is directly integrated into the coat with a zippered pouch that allows for its storage. The SCBA is a Scott NXG2 Airpak with 45-min rated carbon cylinder and integrated SEMS system that uses a quick-disconnect, dual EBSS, EZ-FLO Plus regulator. The SCBA assembly meets the NFPA-1981, 2002 edition requirements and is NIOSH CBRN approved. While designed of the same materials, the differences in features

Fig. 1 Details of the prototype ensemble advanced features, sleeve-glove interface (**a**), hose attachment to jacket (**b**), integrated hood with face piece gasket (**c**), and boot-pants interface (**d**) (Morning Pride Manufacturing, Dayton, OH, USA)

for both standard and prototype ensembles are significant in that the prototype ensemble includes interfaces and components that are not found in conventional, standard ensembles. The objective of the design changes incorporated into the prototype ensemble is to provide improved protection primarily to prevent inward leakage of chemical, biological, or radiological particulate hazards with lowest penalties for increased bulk and weight of the ensemble.

Experimental conditions

Because moisture (e.g., sweat) may alter the interaction between skin and material, as well as the flexibility and motion of fabric, each ensemble was evaluated under dry and wet conditions. The dry condition required the subject to don the assigned ensemble under ambient laboratory conditions of temperature (22 ± 0.5°C) and humidity (40 ± 10%). The wet condition required that the subject was misted with 1.7 l of tepid water. This volume was representative of a 1 h sweat rate during vigorous firefighting activities. The tepid water was applied while the subjects were in undergarments only, after which the assigned ensemble was donned. Subjects started the test 10 min after donning the ensemble to allow time for the water to soak into the lining of the ensemble.

The ergonomic evaluation was performed in two distinct testing phases; first phase was completed before the ensembles had undergone any other testing, brand new ensembles (eight subjects completed this phase); second phase was performed after five wearings of the ensembles (six subjects from the original group completed this phase). Between each phase, five tests were carried out with each ensemble that allowed for comparisons of the garments before and after multiple uses. These tests consisted of treadmill walking for up to 45 min each test within an environmental chamber (22 ± 0.1°C; humidity 50 ± 1%) and were used to assess physiological differences among ensembles. Differences in ergonomic measurements before and after the multiple use testing can be attributed to ensemble wear. The physiological testing carried out between the ergonomic phases addressed the physiological impact of the PE relative to the SE (physiological results to be presented elsewhere).

Subjects donned the SE or PE in either dry or wet conditions, on separate days, to perform the following five tests: baseline (no ensemble), SE-dry, SE-wet, PE-dry, and PE-wet. The order of tests was randomly assigned to negate ordering effect. Subjects underwent baseline ergonomic assessment while wearing clothes similar to those usually worn under firefighter turnout gear. This included a cotton tee-shirt and cotton/denim athletic shorts.

Measurements

Measurements included anthropometrics, static-, dynamic-ROM, and subjective perceptions of comfort. Each test followed a previously-described ergonomics protocol (Johnson 2005) detailed on the experimental procedures section. All measurements were taken in ambient laboratory conditions. For all tests, measurements were taken in the same progressive order as during the baseline data collection session. Measurements progressed from anthropometrics to static ROM, to dynamic ROM, with job-specific ROM assessed after general ROM. Subjective perceptions were taken before and after testing.

Anthropometric measurements were made using standard instruments including a flexible tape measure, circumference tape, washable marker, and scale. To standardize each measurement, three repeated values were taken on the side of the body coinciding with the subject's dominant hand. An average (reported in cm) of the measured values is the reported measurement for each subject ("Results").

Static- and dynamic-ROM was assessed using a goniometer, digital timing system, multi-colored tape (for marking purposes), tape measure, ladder, weighted rescue mannequin (68.2 kg), obstacles, and a weighted object (10.8 kg). The reported value was an average of the three-recorded values.

Each test included an assessment of the subject's reported comfort while wearing both the SE and PE. This was accomplished by combining two visual analog scales with related multiple choice questions. Two 25 cm visual analog scales were administered to the subject, one scale to assess comfort and one scale to assess discomfort, before and after each session. The scales consisted of a line with the words "none" and "maximal" at the extremes. Subjects marked the line accordingly with the question, comfort or discomfort. Each scale was followed with a question about the factor most important to this rating. The visual analog scale results were scored by overlaying a transparent scoring sheet onto the given value, from 0 for "none" to 100 for "maximal". The numerical value of the score was assigned as the assessed value.

Experimental procedures

All dynamic and static activities were clearly explained to the subject and demonstrated by experienced laboratory technicians before a measurement was taken. Static ROM consisted of measuring the active flexion/extension/abduction of the main body joints: elbow, shoulder, neck, hip, knee, ankle and wrist. Other ROM measured consisted of reaching forward as far as possible from sit and stand positions, as well as reaching overhead. General dynamic ROM included the following objective timed motions: kneel and rise, seated squats and step-ups. During job-specific ROM, subjects also performed the following objective timed tests: ensemble donning/doffing, one-arm search, ladder pick-up, crawling over and under objects, mannequin drag, and solid object lift. All these tests were timed; the one-arm search was also measured by the number of knee strides (i.e., crawling on the knees) to cover the given distance, to assess any restriction of motion between ensembles. Subjective questionnaires on perceptions of comfort used on firefighters previously (Stull and Duffy 2000) were completed prior to, and after, each test.

Statistical analyses

Changes in ROM, job specific tasks, and subjective perceptions, between sessions (baseline, SE-dry, SE-wet, PE-dry, PE-wet) were analyzed by means of repeated measures analysis of variance (ANOVA) using the SPSS 15.0 statistical package, with Greenhouse–Geisser correction for heterogeneity of variance. Post-hoc pairwise comparisons were carried out using the least significant differences statistic set at $P < 0.05$ for those analyses in which statistically significant main effects were found. The data used in the analyses were the mean values for three measures obtained for each test.

Results

Anthropometrics measurements

A summary of these measures shows that both ensembles add the same increase to height compared to no-ensemble (14 cm). Subjects wearing the PE weighed 1 kg more than when wearing the SE. Other measures that were taken for baseline (BL), SE, and PE are as follows ($N = 8$): neck to crotch, BL 65.7 ± 4.4 cm, SE 69.2 ± 4.6 cm, PE 69.5 ± 5.1 cm; hip breadth BL 101.4 ± 11.1 cm, SE 125.0 ± 7.5 cm, PE 124.1 ± 8.0 cm; chest circumference BL 96.28 ± 9.1 cm, SE 117.69 ± 8.3 cm, PE 119.13 ± 9.1 cm; waist circumference BL 85.03 ± 10.8 cm, SE 118.00 ± 12.4 cm, PE 121.25 ± 7.6 cm; thigh circumference BL 56.25 ± 4.8 cm, SE 72.56 ± 5.0 cm, PE 72.13 ± 5.1 cm; upper arm BL 31.50 ± 3.1 cm, SE 48.81 ± 6.1 cm, PE 49.81 ± 5.1 cm.

Phase 1

Range of motion

Range of motion was determined from 17 measures of the main joints and motions of the body summarized on Table 1. Numerous baseline (non-ensemble) tests were significantly different from the ensemble tests. There was a significant reduction ($P < 0.05$) of elbow flexion for SE-wet condition compared to the PE-dry and PE-wet conditions; there was also a significant reduction ($P < 0.05$) of wrist flexion and extension for PE-dry condition compared to the same SE-dry condition. Cervical rotation was also lower for the PE compared to the SE without being statistically significant.

Job-specific tasks

Twelve measures of job-specific tasks are summarized in Table 2. Baseline (non-ensemble) tests were significantly different from the ensemble tests on one-arm search (time and strides), as well as object lift tests. There was a significant reduction ($P < 0.05$) of time in the mannequin drag test for SE-wet condition compared to the PE-wet conditions; there was also a significant increase ($P < 0.05$) of time donning the PE-wet compared to SE-dry and SE-wet.

Subjective perceptions

Comfort and discomfort were rated before and after each test. The results of the ratings are summarized on Table 3.

Table 1 Summary of ROM measurements

Measure	Phase 1 (n = 8)					Phase 2 (n = 6)				
	Baseline	SE-dry	SE-wet	PE-dry	PE-wet	Baseline	SE-dry	SE-wet	PE-dry	PE-wet
Elbow flexion (deg)	128.6 ± 17.6	113.3 ± 14.9	114.6 ± 10.4^{d,e}	120.5 ± 12.0^{c}	119.2 ± 8.2^{c}	131.9 ± 8.2^{2,3,4}	118.8 ± 3.8^{1}	115.1 ± 7.9^{1}	117.7 ± 7.1^{1}	113.5 ± 22.5
Shoulder flexion (deg)	161.5 ± 10.5^{b,d,e}	138.7 ± 29.1^{a}	144.6 ± 23.3	128.2 ± 25.6^{a,4}	137.3 ± 21.5^{a}	163.2 ± 19.8	153.8 ± 17.2	148.9 ± 22.5^{5}	151.6 ± 27.9^{d}	156.8 ± 21.5^{3}
Shoulder abduction (deg)	137.4 ± 29.1	110.7 ± 29.3^{c}	122.9 ± 25.6^{b}	108.9 ± 26.1^{4}	112.6 ± 22.4	132.9 ± 19.4	123.6 ± 19.1	122.6 ± 20.4^{5}	125.3 ± 25.9^{d}	132.2 ± 18.5^{3}
Wrist flexion (deg)	56.4 ± 10.1^{c,d}	51.5 ± 13.1^{d}	45.0 ± 8.9^{a}	43.7 ± 9.8^{a,b}	45.1 ± 9.0	60.0 ± 6.3^{2,4,5}	48.3 ± 5.6^{1}	49.4 ± 7.2	50.4 ± 6.1^{1}	45.6 ± 7.4^{1}
Wrist extension (deg)	52.7 ± 11.8^{d,e}	44.2 ± 10.0^{d}	44.5 ± 15.5	41.5 ± 10.4^{a,b}	41.0 ± 7.1^{a}	50.7 ± 10.3^{3,4,5}	46.8 ± 11.1^{5}	41.3 ± 9.1^{1}	38.7 ± 9.3^{1}	38.1 ± 9.4^{1,2}
Knee flexion (deg)	118.5 ± 28.6	116.8 ± 10.1	115.5 ± 9.0	117.3 ± 8.0	108.8 ± 7.9	132.0 ± 8.9	126.6 ± 7.0	121.8 ± 10.2	122.0 ± 4.9	121.4 ± 8.6
Ankle dorsiflexion (deg)	31.7 ± 14.5^{e}	22.3 ± 8.4	18.8 ± 4.1	18.4 ± 11.2	17.4 ± 6.2^{a}	19.3 ± 4.5	16.5 ± 4.3	20.6 ± 3.5	18.4 ± 5.4	20.9 ± 5.3
Ankle plantarflexion (deg)	27.8 ± 11.8	21.3 ± 4.0	25.7 ± 10.3	18.4 ± 8.1	19.3 ± 4.5	35.4 ± 8.9^{2}	25.1 ± 8.0^{1}	27.2 ± 9.1	27.1 ± 7.6	28.4 ± 7.9
Cervical rotation (deg)	53.5 ± 9.9^{b,c,d,e}	35.2 ± 16.4^{a}	35.5 ± 11.8^{a,d}	30.2 ± 15.4^{a,c}	31.4 ± 14.7^{a}	61.8 ± 9.6^{2,3,4,5}	53.0 ± 9.2^{1,4,5}	55.9 ± 11.2^{1,4,5}	42.9 ± 4.5^{1,2,3}	44.0 ± 6.3^{1,2,3}
Cervical flexion (deg)	38.9 ± 13.6^{b,d}	22.7 ± 9.1^{a}	23.8 ± 8.0	20.0 ± 12.1^{a}	25.1 ± 8.2	41.5 ± 8.6^{2,4,5}	29.3 ± 7.1^{1}	33.5 ± 8.6	29.4 ± 8.1^{1}	30.3 ± 10.9^{1}
Trunk extension (deg)	32.4 ± 22.5	22.6 ± 3.5	20.7 ± 5.9	22.3 ± 4.2	21.0 ± 9.9	24.8 ± 5.1^{5}	21.6 ± 5.1	19.9 ± 1.5	20.7 ± 4.6	18.1 ± 1.9^{1}
Trunk flexion (deg)	99.4 ± 26.0	98.5 ± 23.5	95.0 ± 22.1	98.8 ± 20.8	100.5 ± 14.9	101.7 ± 17.1	103.8 ± 10.4	108.3 ± 2.9	107.3 ± 7.1	107.6 ± 5.1
Trunk lateral flexion (deg)	25.1 ± 5.5^{b,d}	21.4 ± 5.2^{a}	22.7 ± 4.6	18.8 ± 4.8^{a,e}	23.9 ± 5.7^{d}	29.9 ± 6.1^{5}	26.2 ± 4.4	24.2 ± 5.3	26.0 ± 2.4	21.6 ± 4.4^{1}
Sit and reach (cm)	25.1 ± 9.3^{d,e}	16.7 ± 5.6	18.0 ± 5.2^{d}	15.3 ± 4.5^{a,c}	16.1 ± 4.1^{a}	24.0 ± 4.6^{2,3,5}	17.9 ± 5.0^{1}	17.1 ± 4.9^{1}	18.5 ± 7.5	16.5 ± 4.4^{1}
Stand and reach (cm)	11.6 ± 2.6^{b,c,d,e}	7.9 ± 2.2^{a}	8.3 ± 1.8^{a}	8.2 ± 1.8^{a}	8.4 ± 2.2^{a}	9.8 ± 1.9^{2,4,5}	7.3 ± 0.6^{1}	7.9 ± 0.7^{4}	6.9 ± 0.5^{1,3}	7.0 ± 0.7^{1}
Overhead reach (cm)	220.1 ± 13.4	219.7 ± 12.4	219.7 ± 12.5	217.0 ± 13.4	218.5 ± 13.0	218.3 ± 13.6	218.8 ± 13.6	214.1 ± 8.4	217.1 ± 14.2	218.1 ± 12.5

Superscripts indicate statistically significant differences ($P < 0.05$) between tests; Phase 1: baseline = a; standard dry = b; standard wet = c; prototype dry = d; prototype wet = e; Phase 2: baseline = 1; standard dry = 2; standard wet = 3; prototype dry = 4; prototype wet = 5

Table 2 Summary of job specific task measurements

Measure	Phase 1 (n = 8)					Phase 2 (n = 6)				
	Baseline	SE dry	SE wet	PE dry	PE wet	Baseline	SE dry	SE wet	PE dry	PE wet
Kneel and rise one knee (s)	7.5 ± 1.3	7.0 ± 2.5	6.7 ± 1.4^{e}	7.0 ± 2.1	7.3 ± 1.4^{c}	5.5 ± 1.2	6.0 ± 1.5	5.5 ± 1.0	6.1 ± 1.5	5.9 ± 1.3
Kneel and rise both knees (s)	10.6 ± 1.8	10.5 ± 2.8	10.3 ± 1.9	11.1 ± 2.9	10.6 ± 1.8	8.4 ± 1.7^{2,4,5}	9.3 ± 1.6^{1}	9.0 ± 1.0	9.6 ± 2.0^{1}	9.3 ± 1.6^{1}
Seated squat (s)	5.5 ± 1.4	5.0 ± 1.4	4.9 ± 1.0	4.9 ± 1.3	5.2 ± 0.9	4.5 ± 1.0	4.4 ± 1.1	4.1 ± 0.6	4.4 ± 1.3	4.4 ± 1.0
Alternating step up (steps/min)	25.2 ± 4.0	25.9 ± 8.9	26.4 ± 5.6	26.2 ± 6.7	25.9 ± 4.3	32.2 ± 6.6^{2,4,5}	29.6 ± 6.7^{1}	30.6 ± 6.7	28.8 ± 7.7^{1}	28.8 ± 6.0^{1}
One arm search (strides/distance)	15.0 ± 2.9^{b,c,d,e}	12.4 ± 2.8^{a}	12.4 ± 2.4^{a}	12.5 ± 2.9^{a}	11.7 ± 1.8^{a}	13.9 ± 2.5^{2,3,4,5}	11.6 ± 2.5^{1}	11.6 ± 1.5^{1}	11.7 ± 2.1^{1}	11.5 ± 1.8^{1}
One arm search (s)	23.5 ± 6.6^{b,c,d,e}	14.3 ± 4.4^{a}	13.9 ± 3.5^{a}	15.7 ± 7.4^{a}	14.3 ± 2.9^{a}	19.9 ± 6.4^{2,3,4,5}	13.5 ± 3.4^{1}	13.5 ± 3.5^{1}	12.2 ± 4.8^{1}	14.0 ± 2.7^{1}
Ladder pickup (s)	6.8 ± 2.8	5.7 ± 1.2	6.2 ± 1.2	6.0 ± 1.4	6.1 ± 1.1	4.9 ± 0.7	5.1 ± 0.8	5.0 ± 0.7	6.0 ± 1.3	5.0 ± 0.7
Crawl over/under objects (s)	10.4 ± 3.9	9.1 ± 3.4	9.1 ± 2.6	9.8 ± 4.6	9.1 ± 2.3	8.4 ± 1.8	7.9 ± 2.0	8.1 ± 2.0	7.8 ± 1.8	8.1 ± 2.1
Mannequin drag (s)	5.1 ± 1.5	5.7 ± 2.1	5.1 ± 1.7^{e}	5.9 ± 2.3	6.9 ± 3.2^{c}	4.0 ± 0.7	4.4 ± 1.6^{4}	4.7 ± 1.5	5.1 ± 2.0^{2}	4.8 ± 2.2
Objects lift (s)	10.6 ± 3.2^{b,d,e}	8.5 ± 2.4^{a}	8.7 ± 2.3	8.6 ± 2.3^{a}	8.5 ± 2.5^{a}	7.6 ± 1.2^{2}	7.1 ± 1.5^{1}	7.0 ± 1.6	7.3 ± 1.7	7.2 ± 1.6
Donning (min)	n/a	4.3 ± 2.3^{e}	4.4 ± 2.6^{e}	6.0 ± 4.3	5.7 ± 3.0^{a,b}	n/a	3.1 ± 1.9	3.6 ± 2.4	4.1 ± 2.9	3.4 ± 1.7
Doffing (min)	n/a	2.4 ± 1.3	2.1 ± 1.0	2.4 ± 0.9	3.3 ± 3.1	n/a	1.3 ± 0.4	1.3 ± 0.5	1.6 ± 0.4	1.8 ± 0.8

Superscripts indicate statistically significant differences ($P < 0.05$) between tests; Phase 1: baseline = a; standard dry = b; standard wet = c; prototype dry = d; prototype wet = e; Phase 2: baseline = 1; standard dry = 2; standard wet = 3; prototype dry = 4; prototype wet = 5

Comfort was rated higher in the SE than the PE. There was a significantly higher rating of comfort ($P < 0.05$) at the end of the session for the SE-wet condition compared to PE-dry and PE-wet conditions. The discomfort was rated significantly lower ($P < 0.05$) for the SE-dry compared to the SE-wet and PE-wet conditions at the end of tests. Most subjects expressed complaints regarding the various areas of the ensemble discomfort. Subjects in general disliked the PE reinforced jacket zipper and the hose attachment connecting the SCBA to the jacket. They also complained about the weight of the SCBA, the weight of the garment, and the heat within the ensemble, for both the PE and SE.

Phases 1 and 2 combined

Range of motion

Table 1 summarizes all the results for the ROM measurements across sessions comparing phases 1 and 2. As can be seen, the subjects' mobility improved with the use of the ensembles and all the tests showed a greater mobility between phases 1 and 2. Only a few showed statistical significance between the phases (Table 1).

Job-specific tasks

Table 2 summarizes all the results for the job-specific measurements across sessions comparing phases 1 and 2. Following the same trend shown in the ROM, subjects performed the tests faster after several uses of the ensemble, probably due to the ease of moving in the ensemble after "breaking it in" with several wearings. Training might also have had an effect on phase 2 even though it was minimized through the randomization of the ensemble test in each phase. No significant differences were found other than the baseline test compared to ensemble tests on one arm search test.

Subjective perceptions

Both comfort and discomfort were still rated higher and lower, respectively, in the SE than the PE during pre- and post-test questionaries. There were no significant difference between the ratings in phases 1 and 2. Nevertheless, the ratings of comfort (pre- and post-test) were higher across sessions during phase 2. Discomfort was also rated lower across sessions during phase 2. Following the trend that was observed on the results of the job specific tasks, subjects felt more comfortable during the second set of tests when the ensemble was used several times. Here

Table 3 Summary of subjective perception ratings

Measure (0–100)	Phase 1 (n = 8)				Phase 2 (n = 6)			
	SE-dry	SE-wet	PE-dry	PE-wet	SE-dry	SE-wet	PE-dry	PE-wet
Pre-test comfort	64.3 ± 22.6	71.0 ± 19.3^{c}	61.8 ± 17.7^{b}	62.5 ± 18.1	75.8 ± 19.1	78.9 ± 17.4	68.8 ± 15.1	68.1 ± 13.2
Post-test comfort	57.0 ± 27.2	57.0 ± 27.1^{d}	52.2 ± 25.2	42.1 ± 21.5^{b}	53.5 ± 22.1	72.0 ± 18.6^{3,4}	53.0 ± 11.2^{2}	50.6 ± 10.9^{2}
Pre-test discomfort	34.2 ± 27.2	28.8 ± 22.2	30.7 ± 15.7	36.6 ± 13.2	26.8 ± 19.6	21.9 ± 16.2^{4}	28.6 ± 15.6	35.5 ± 13.2^{2}
Post-test discomfort	42.1 ± 24.9^{b,d}	50.0 ± 24.1^{a}	49.3 ± 22.5	60.8 ± 21.6^{a}	44.8 ± 20.5	30.2 ± 15.1^{3,4}	53.1 ± 14.2^{2}	54.1 ± 19.4^{2}

Superscripts indicate statistically significant differences ($P < 0.05$) between tests; Phase 1: standard dry = a; standard wet = b; prototype dry = c; prototype wet = d; Phase 2: standard dry = 1; standard wet = 2; prototype dry = 3; prototype wet = 4

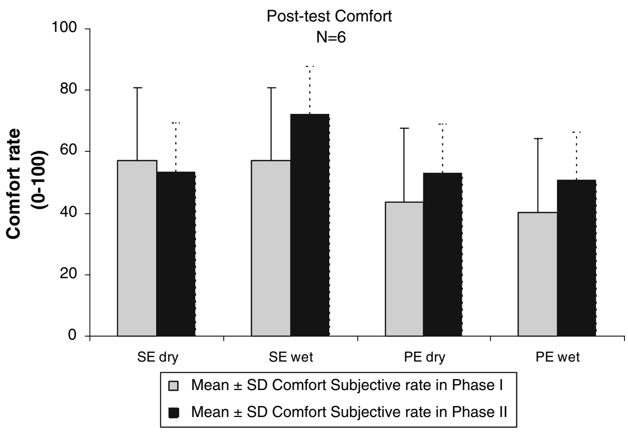

Fig. 2 A comparison between standard ensemble (*dry*), standard ensemble (*wet*), prototype ensemble (*dry*), and prototype ensemble (*wet*) in post-test comfort during phase I and II (N = 6)

again, a training effect could account for some of the differences between the two phases, since the subjects knew what to expect in phase 2. Figure 2 shows the comfort rating at the end of the sessions comparing phases 1 and 2.

Discussion

At the outset of the study, we hypothesized that there would be no significant differences between the SE and the PE. The lack of significant differences among most of the measurements comparing the SE and PE supports our hypothesis. A possible reason for this finding is that the standard ensemble served as the basic platform for the development of the prototype. Using a similar methodology for ROM, Huck (1988) found significant differences between different designs. However, he recognized, as we do, that measurements of joint motion taken over bulky protective clothing is a challenge and need to be carefully obtained. Nevertheless, we found a few ergonomic differences between the SE and PE. These differences between the standard and prototype ensembles are related to the sleeve–glove magnetic ring interface, reinforced jacket zipper, facemask-hood seal interface, and the hose attachment connecting the SCBA to the jacket. For phase 1, there was a decrease in ROM at the wrist and neck comparing the SE and PE, probably due to the fact that the PE was modified with a magnetic ring closure between the glove and the sleeve, and incorporation of a hood and a hose attached to the jacket (Table 1). It seems that those differences were not significant after several uses of the ensembles (i.e., after the garment was "broken in"). In general, ROM measurements were greater after several uses of the ensembles (phase 2). These results suggest that protective ensembles may be worn several times for training or other purposes to improve ROM before using it in the field. The only difference that remained significant was the decrease in cervical rotation which was probably due to the hose attachment from the facepiece to the jacket (Table 1). The objective of the design changes incorporated into the prototype ensemble is to provide improved protection by limiting inward leakage of chemical, biological, or radiological particulate hazards with lowest impact on the bulk and weight of the ensemble. This objective was achieved in the present PE with a minor restriction of movement. Obviously more ROM is better, but these minor restrictions that the PE imposes may not be that critical functionally, as shown in the job-related tasks (Table 2), and still provide the wearer with a greater additional protection than the SE. In addition, for the most part, the job-specific tasks did not show significant differences in ROM suggesting that the PE does not affect overall mobility (Table 2).

Our survey of the existing literature found few articles related to the methodology we used thereby making it difficult to compare our results to other related research. In this part of the testing, it should be mentioned that the mannequin drag test took longer for the PE compared to the SE in phase 1 (Table 2). This increase in time to drag the mannequin in the PE seemed to be due to the glove–sleeve interface because subjects could not easily place their hands and wrists under the mannequin axillary area as they did with the SE. Moreover, the donning/doffing procedures were significantly longer because extra features of the prototype ensemble increased the number of actions required for donning and doffing. All the job-specific tasks took shorter times in phase 2 (Table 2). Again, the results suggest that wearing the ensembles several times improves mobility of the wearer.

In terms of comfort, subjects rated the SE more comfortable than the PE. Barker et al. (2000) and Stull and Duffy (2000) used similar questionaries and concluded that subjects could differentiate between ensembles by their level of comfort. Our research also found that subjects preferred the SE over the PE based on their comfort level (Table 3). This slight preference was probably due to the fact that the SE did not impose additional stressors that accompanied the modifications made to the PE. The pretest comfort ratings did not show statistical differences, but a trend of increased comfort wearing the SE (Table 3). Subjects rated the SE more comfortable than the PE after finishing the sessions. Following the same results as previous testing, when the subjects rated comfort during phase 2, the ratings were higher than phase 1. The comfort level was higher after several uses of the ensemble (Table 3). Subjects in general disliked the reinforced jacket zipper and the hose attachment connecting the SCBA to the jacket. They also complained about the weight of the SCBA, the weight of the garment, and the heat within the ensemble, for both the PE and SE.

It is important to point out that the prototype ensemble continued to evolve as part of a separate development project. Feedback from the findings discovered in this study supported changes to the prototype design that identified specific design problems. For example, improvements were made in the glove ring design to lower its profile and decrease the rigidity of the sleeve–glove interface. In addition, the diameter of the hose used in the hose–facepiece interface has been decreased with repositioning of the hose to minimize effects on head movement. While the benefit of these design improvements have not been verified experimentally, the identification of specific ergonomic factors related to the prototype ensemble design was made possible through this study. These overall findings support the value of a comprehensive ergonomic evaluation of protective clothing systems to ascertain human factors issues.

Conclusions

Firefighter ensembles limit wearer movement to some extent. The data collected in this study suggest that, in spite of design features to enhance chemical/biological hazard protection, the PE design does not adversely affect the wearer's overall functional mobility compared to the SE. Comfort was higher in the SE than the PE, suggesting that some of the new features might account for that difference. Furthermore, the turnout gear interface seals necessary to provide the elevated protection against chemical/biological hazards did not seem to introduce a significant additional ergonomic "burden" to firefighters, but might be more uncomfortable to use. Therefore, this study was able to identify specific areas in which differences were found between ensembles to permit further attention in the design process to guide improvements to the prototype.

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