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IMPACTS OF INDIVIDUAL PROTECTIVE EQUIPMENT ON ACTIVE RANGE OF MOTION AND RESPIRATORY PROTECTION

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14. ABSTRACT
This investigation quantified active range of motion (AROM) of common military and law enforcement movements while wearing chemical/biological (CB) and ballistic protective equipment, measured the impacts of integrated CB and ballistic equipment on respirator protection from particulates, and determined local head and neck protection factors against gases and vapors with the same individual protective equipment (IPE). To quantify the impacts of IPE wear on AROM, sequential levels of protective equipment items were added to the test matrix to simulate differing levels of respiratory and ballistic protection. Wearing an air-purifying respirator alone did not significantly impact head AROM. However, substantial reductions in head AROM, mainly cervical rotation, were evident with the addition of the CB suit, ballistic protective helmet, and body armor. Reductions in AROM for regions other than the head were found primarily for body armor test conditions. Despite these notable decrements in head and body mobility, with increasing levels of protective equipment wear, respiratory protection levels were relatively consistent among IPE test conditions. Therefore, interactions among CB and ballistic IPE items will cause some reduction in mobility but should not compromise respiratory protection.

15. SUBJECT TERMS

Individual protective equipment	Helmet	Respiratory protection
Respirator	Body armor	Aerosol
Chemical/biological suit	Active range of motion	Man-in-simulant test

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PREFACE

The work described in this report was authorized under Project Nos. 6N3YP2, Head-Borne PPE Mass Properties Standards, and 6N3YNA, NIST In-mask Vapor Leakage Standards Development. This work was started in February 2007 and completed in September 2007.

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IMPACTS OF INDIVIDUAL PROTECTIVE EQUIPMENT ON ACTIVE RANGE OF MOTION AND RESPIRATORY PROTECTION

1. INTRODUCTION

The type and range of motion about any given body joint depends upon the structure of the joint and the number of its axes, the restraints imposed by ligaments and muscles crossing the joint, and the bulk of adjacent tissue.[1] Range of motion is also impacted by restraints imposed by individual protective chemical and biological (CB) equipment items and ballistic protective equipment.[2] Hindrances on movement can be detrimental, even life threatening, to military and emergency response personnel. Even so, there is little empirical data that quantifies movement restrictions due to wear of individual protective equipment (IPE). This paucity of information inhibits equipment design advances to alleviate IPE movement restrictions and prevents any improvements in end-user mobility when IPE must be worn. Because IPE should meet the needs and requirements of the end users, range of motion information needs to be gathered during movements that emulate those related to common user tasks, which can support functional design to accommodate special needs of the wearer. For example, a 3.8% to 28.7% increase in range of motion while wearing protective overalls has been associated with design features that allow for more mobility.[3]

During normal operations, many law enforcement personnel must wear a duty uniform that generally consists of a shirt, trousers, and boots. Some missions may also include wear of ballistic protective helmets and vests. During operations in a chemically contaminated environment, a police officer will likely have to don a special chemical protective suit, gloves and a protective respirator. These configurations are very similar to those required of U.S. Army combat soldiers. Whereas a significant amount of data have been gathered to assess the protection afforded by chemical and biological individual protective equipment (CB IPE), very little is known about the impacts of non-chemical IPE items on protection when they are added to the CB protective ensemble. That is, past research has focused on the protective levels of complete protective ensembles and has not adequately evaluated the influence of other protective equipment on the performance of the CB protective ensemble. Other items such as helmets, head-mounted night vision goggles, and body armor may exert an indirect yet substantial effect on protection levels afforded by standard ensembles. The limited data that are available focus primarily on military IPE and protection against chemical aerosol challenges. Although important, the existing data cannot provide any information with regard to the impacts of non-chemical IPE on protection from chemical vapor challenges.

The purposes of this investigation were to 1) determine normal values for active range of motion (AROM) of individuals performing common military and law enforcement movements and to quantify the impacts of wearing individual CB and ballistic protective equipment on AROM, particularly for head borne items; 2) quantify the impacts of integrated CB and ballistic IPE on respirator protection from particulates while performing these common movements; and 3) determine local head and neck protection factors against gases and vapors for individuals performing the same movements while exposed to a simulated vapor challenge.

2. METHODS

2.1 Quantification of Active Range of Motion with IPE

2.1.1 Experimental Procedures

Ten subjects (eight males and two females) between the ages of 18 and 46 (35 ± 9 yr) participated in this part of the study. All volunteers were civilians employed at the ECBC with substantial experience with respirator wear. Volunteers were thoroughly briefed on the nature and purpose of the study and signed informed consent was obtained upon completion of all volunteer agreement paperwork. Each volunteer also completed the Occupational Health and Safety Administration (OSHA) Regulation 29 CFR 1910.134 Respirator Medical Evaluation Questionnaire and was cleared for respirator wear and testing upon review by medical professionals of the Troop Medical Clinic, Edgewood Area, APG.

The specific IPE configurations that were tested are listed in Table 1 and presented in the Appendix. The Millennium CBRN respirator was worn for all conditions requiring respirator wear. The Millennium is a full-face piece, air-purifying respirator (APR) similar to the U.S. Air Force and U.S. Navy MCU-2/P gas mask. The active wear clothing conditions involved wear of T-shirts, shorts, socks and sneakers, which each subject was instructed to bring with them to the test facility. A Tychem® SL - High Performance Level B Chemical Suit, with an integral hood, elastic wrists closures, and integral boot covers was worn for conditions calling for a CB protective suit. Tychem® SL is a lightweight fabric designed to provide protection against a broad range of industrial chemicals. The Advanced Combat Helmet - Commercial Version (ACH-C) was the ballistic helmet used for helmet wear conditions. This helmet meets U.S. Military ballistic fragment requirements and is compatible with the Millennium respirator. A 0.9 Kg ankle weight was mounted flat to the front of the helmet to create the weighted helmet condition. The BlackHawk® S.T.R.I.K.E. Cutaway Tactical Armor Vest was utilized for conditions calling for ballistic vest wear. This vest is lightweight (1.6 Kg) with an adjustable waist and shoulder system for tailoring girth and torso length for improved fit. A neck collar and yoke, designed for added ballistic protection for the back and front of the neck, respectively, was added to the vest for one test condition. Finally, a pistol belt and holster carrying a mock pistol was worn around the waist for all test conditions. Each subject was sized and fitted for all IPE items by an experienced test administrator before testing began.

Table 1. AROM Experimental Test Conditions

Condition	IPE Configuration
Control	Active wear clothing without IPE
Mask	Respirator with active wear clothing
Suit	Respirator and CB suit
Helmet	Respirator, CB suit, and ballistic helmet
Helmet+weight	Respirator, CB suit, and front weighted ballistic helmet
Armor	Respirator, CB suit, ballistic helmet, and ballistic vest
Armor+collar	Respirator, CB suit, ballistic helmet, and ballistic vest with neck collar and yoke

Upon arrival to the lab, subjects changed into active wear clothing and were prepped for testing. First, a Millennium respirator, Tychem® SL suit, and ACH-C helmet were properly sized and assigned to a subject by test facility personnel. Subjects then donned nine body-mounted range-of-motion sensors for measuring the position and orientation of specific body parts during AROM testing. Active range of motion was measured using the MotionStar™ Wireless system (Ascension Technology Corporation, Burlington, VT). MotionStar™ is a six degree-of-freedom measurement system that uses pulsed direct current magnetic fields to simultaneously track the position and orientation of sensors located on individuals within ten feet of a transmitter. The system consists of body mounted sensors, body mounted electronics and a base station. There are no wires from the user's body to the base station. The user was completely free to move about without a trailing cable.

Each sensor measured the position and orientation of the specific body part to which it was attached. Sensors consisted of a 1-in. cube attached via a wire to an electronics unit that was mounted in a cloth pouch attached to a backpack. Sensors were attached to sensor mounts on stretchable bands that went around the head, legs, and arms. Sensors were mounted in the following nine locations on the body: left and right arms, left and right wrists, left and right legs, back of the head (external occipital protuberance), neck (vertebra prominens), and lower back (median crest of the sacrum) (Figure 1). The neck sensor was mounted using a 6.4 x 8.9-cm bandage and the lower back sensor was attached to a waist mounted belt. Sensor position on the body and within the measuring field was defined by digitization of multiple body landmarks while the subject stood in place. Body landmarks required for AROM system digitization are presented in Figure 1.

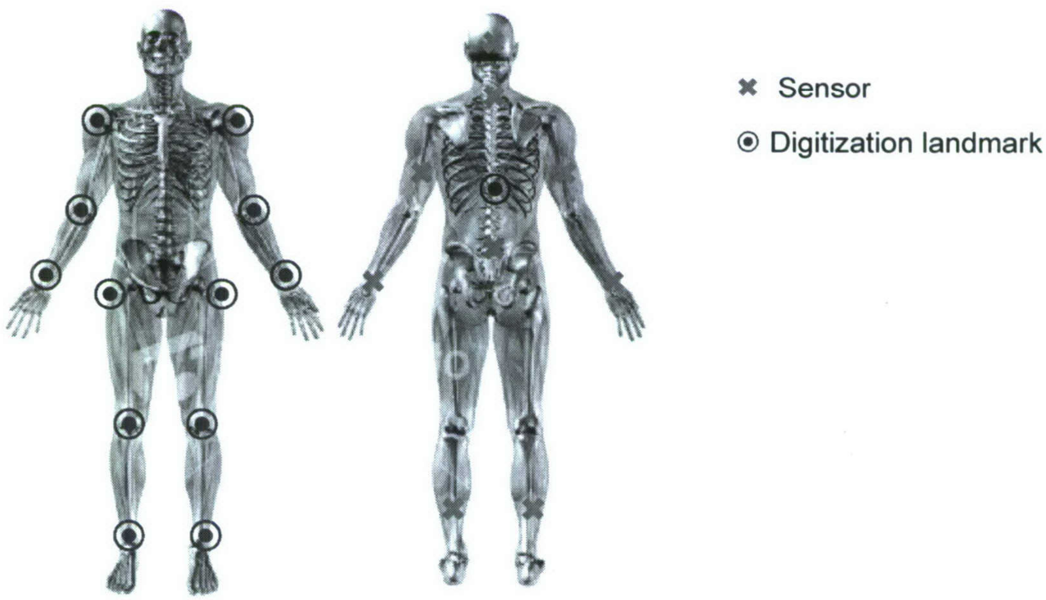


Figure 1. Sensor Placements and Digitizing Landmarks for Measuring AROM

Testing commenced once operation of the AROM equipment was validated. Experimental test conditions were administered in order starting with Control conditions, followed by Mask, Suit, Helmet, Helmet+weight, Armor, and Armor+collar conditions. Test personnel assisted subjects with IPE donning. Active range of motion for various body joints was measured and recorded as test participants performed the movements listed in Table 2.

Test personnel demonstrated how to perform each AROM activity prior to commencement. Subjects were allowed to practice these motions until they felt comfortable performing each exercise and test personnel decided that they were performing the motions proficiently. Each subject performed up to three repetitions of each movement for each test condition. The duration for a single activity was 20 sec and each motion was performed repetitively until the subject was instructed to stop. The movement sequence was arbitrarily selected to ensure consistency when taking AROM measurements.

Subjects were instructed to perform activities until their movements were stopped by muscle tightness or slight discomfort or until a substitution movement occurred. A metronome set at 50 beats/min was used for pacing exercises to have subjects perform them uniformly with the exception of the following: traffic control movements, sitting and standing, shouldering the rifle, sighting the pistol, forward lunge, and climbing stairs. Companion software (The MotionMonitor™, Innovative Sports Training, Inc., Chicago, IL) recorded joint angles during each data collection period. Range of motion results were presented graphically on-screen immediately upon completion of data collection. Subjects rested for 10 mins between test conditions.

2.1.2 Analysis of AROM Data

Data were analyzed according to the primary AROM variable or variables pertinent to the 13 body motions performed during testing. The list of AROM variables analyzed for each AROM exercise is presented in Table 3.

For descriptive statistics, ANOVA were performed to compare AROM results among test conditions based on the individual body activities. AROM performance ratings (AROM PR) were also calculated according to the following equation

$$\text{AROM PR}_{\text{IPE}}\,(\%) = \left(\frac{AROM_{IPE}}{\sum_{i=1}^{n} AROM_{Ci} \big/ n} \right) \times 100 \qquad (1)$$

where $AROM_{IPE}$ = joint range of motion for a given AROM activity and IPE test condition and $AROM_C$ = joint range of motion under Control conditions for the same activity. Performance rating calculations provided estimates of the percentage of performance of each test participant with IPE compared to the non-IPE condition. As such, AROM PR results are relative and scaled between 100 (no performance degradation) and zero (complete performance degradation). Bonferroni's post-hoc analysis was computed to determine significant differences among group means if a significant F statistic was initially obtained. Statistical significance was accepted at the $p < 0.05$ level.

Table 2. Activities/Exercises Used to Assess AROM

Range of Motion Activity	Activity Identifier	Description
Rotate head side-to-side	Head S2S	Standing in place, a subject slowly turned his/her head from side-to-side
Flex head up and down	Head Nod	Standing in place, a subject slowly moved his/her head up and down
Flex head to the left and right	Head Lat Flex	Standing in place, a subject slowly flexed his/her head to the left as if to touch the left ear to the left shoulder and then repeated the motion to the right
Upper arm movements	Arms Up	From a standing position a subject raised both arms sideward and upward with the palms facing forward until the hands touched above the head or moved as far as possible over the head without bending the elbows
Twisting at waist	Twist	While standing, a subject extended his/her arms perpendicular to the sides of torso and twisted at the waist from side-to-side
Traffic control hand & arm movements	Traffic	From a normal standing position, subjects mimicked stopping forward traffic and directing traffic from the side, alternating left and right
Sit and stand repeatedly	Sit	Subjects stood beside a bench, sat down, and then returned to a standing position
Reach for floor and ceiling	Bend & Reach	Standing in place with arms at side, subjects bent at the waist and reached for the floor with both arms extended, returned to standing, fully extended arms above the head, and returned to standing with arms at the side
On hands & knees, turn head side-to-side	H&K-Head S2S	Subjects got into a crawling position on their hands and knees and slowly rotated the head from side-to-side
Shoulder rifle	Rifle	Subjects simulated shouldering a mock rifle and engaging a wall-mounted target while standing
Draw and sight a pistol	Pistol	Subjects simulated removing a mock pistol from a holster and engaging a wall-mounted target while standing
Forward Lunge	Lunge	From a standing position subjects stepped forward as far as possible with one leg, bending the knee about 90 degrees, and holding for 3 sec; subjects then returned to the standing position and repeated the motions with the opposite leg
Climb stairs	Step	Subjects stepped up and down a 23 cm high platform using one foot at a time

Table 3. AROM Variables Analyzed According to Body Motions

Range of Motion Activity	AROM Variables
Head S2S	Left and right cervical rotation; total cervical rotation
Head Nod	Cervical flexion and extension; full range of flexion and extension
Head Lat Flex	Left and right cervical lateral flexion; total lateral flexion
Arms Up	Shoulder abduction
Twist	Left and right thoracic rotation; total thoracic rotation
Traffic	Left and right cervical rotation
Sit	Left and right hip flexion
Bend & Reach	Shoulder flexion and extension; thoracic flexion
H&K-Head S2S	Left and right cervical rotation; total cervical rotation
Rifle	Cervical rotation, flexion, and lateral flexion; shoulder abduction
Pistol	Shoulder flexion and internal rotation
Lunge	Left and right hip and knee flexion
Step	Left and right knee flexion

2.2 Assessment of Respiratory Protection from Particulates

2.2.1 Test Procedures

The impacts of integrated CB and ballistic IPE on respiratory protection from particulates were evaluated at the ECBC Protection Factor Test Facility (PFTF). Testing conditions were in accordance with the Joint Service Standardization for Fit Factor Testing, with a corn oil concentration of 20 – 40 mg/m^3 and a particle size of 0.4 – 0.6 µm. Seven of the ten subjects involved in AROM trials participated in this phase of testing (5 males and 2 females; 37 ± 7 yr). Again, each subject was properly sized for the IPE items prior to testing.

Before entering the aerosol chamber, subjects donned the appropriate equipment and completed a five-exercise (normal breathing, deep breathing, side-to-side head movement, up and down head movement, and facial expressions) mask fit test using a PortaCount® Plus (TSI Incorporated, St. Paul, MN) to ensure an adequate seal of the respirator to the face prior to testing in the aerosol chamber. An overall respirator fit factor of at least 2000 needed to be attained to meet the requirement of an adequate seal.

Up to four subjects were tested in the aerosol chamber at one time. All in-mask sampling was done through the drinking tube of the Millennium and all inner-mask drink tubes were removed to prevent sample blockage. An automated laser photometer quantitative fit testing (QNFT) system determined respirator protection factors associated with the various IPE configurations. The system consisted of a data acquisition system (model 8588, TSI, Incorporated) and four laser photometers (model 8587, TSI, Incorporated). Sampling sequence of the QNFT system was as follows: 1) sampling of chamber aerosol concentration;

2) measurement of photometer background; 3) performance of a high-flow clean air purge of the respirator; and 4) sampling and recording of in-mask aerosol concentration. The flow rate for in-mask sampling was approximately 2.2 L/min. Each respirator QNFT was conducted as subjects completed the same movements that were performed for AROM trials (Table 2) with the following additions: normal breathing, talking out-loud (i.e., reciting the Rainbow Passage), seated rest, and treadmill walking at 1.8 m/s. Each of the activities was performed for 1 min and the metronome was utilized as for AROM testing. During the QNFT routine, respirator protection factor (PF) data were presented graphically in real-time on a computer monitor.

The IPE test conditions assessed in this phase of testing were identical to those presented in Table 1 with the exception of the Control condition. The test matrix was randomized and subjects wore each concept for one trial. Subjects completed two IPE test conditions before doffing their respirator and resting for 15 min. The five-exercise mask fit test was repeated prior to re-entering the chamber each time a mask was re-donned.

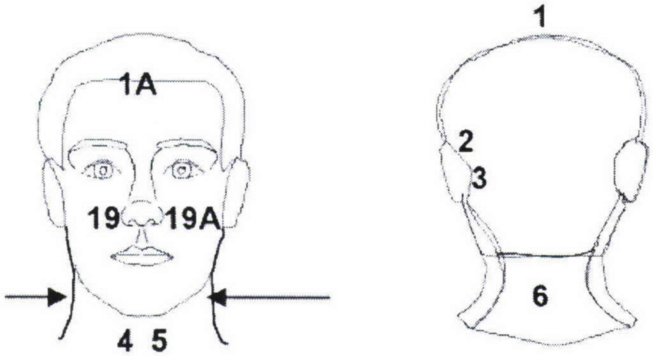
2.2.2 Analysis of Aerosol Protection Factor Data

One-minute average PFs were recorded for each exercise and an overall PF was derived upon the completion of the 16-min trial based on the harmonic average of the PF values for each exercise. All PF data were log transformed for statistical analysis. Results were compared among IPE conditions by AROM activity and for overall PF using ANOVA.

2.3 Evaluation of Protection from Gases and Vapors

The impacts of integrated CB and ballistic IPE on face, head, and neck protection from gases and vapors were evaluated at the ECBC Man-in-Simulant Test (MIST) facility. Testing conditions followed guidelines published in the U.S. Army Test Operating Procedure (TOP) 10-2-022 and the American Society for Testing and Materials (ASTM) Standard F 2588-06.[4,5] Four of the subjects involved in both the AROM and aerosol PF trials participated in this phase of testing (3 males and 1 female; 33 ± 7 yr). Again, each subject was properly sized for the IPE items prior to testing.

Upon arrival to the lab, subjects were required to drink at least 300 mL of water before IPE donning commenced. Subjects prepped for testing by entering an environmentally controlled two-stage clean room where they were fitted with passive adsorbent dosimeters (PADs). The clean room was used to don and doff the IPE ensembles and PADs without contaminating the samplers. The PADs are patches backed with medical adhesive and made of an absorbent material to collect any chemical vapor simulant challenge that happens to infiltrate a protective ensemble. Nine PADs were placed on the skin or hair at the locations depicted in Figure 2. Once all PADs were positioned, subjects dressed in the scheduled IPE configuration with assistance from test personnel. After the ensemble was donned, each subject's garments were checked to ensure proper closure and fit. The subjects then proceeded directly into the exposure chamber.



PAD Locations

1 – scalp
1A – forehead
2 – behind left ear up
3 – behind left ear
4 – neck right
5 – neck left
6 – nape of neck
19 – right cheek
19A – left cheek

Figure 2. PAD Placements for Measuring Gas/Vapor Exposures to the Face, Head, and Neck

The exposure chamber measured 12.2 m long, 6.1 m wide, and 4.3 m high and was equipped with a purge and containment system for vapor challenge testing. A 100 mg/m^3 methyl salicylate (MeS) challenge was generated and maintained in the chamber by a vapor generator connected to a controller, a simulant transfer pump, and gas analyzers in a closed loop feedback system. The chamber concentration was raised to the required 100 mg/m^3 MeS challenge and stabilized at this level before subjects were ready to enter the chamber. Vapor levels and temperature in the chamber and clean room areas were monitored and recorded continuously by a computer data acquisition system.

Once prepped for testing, one subject pair entered the chamber through an airlock. The second subject pair entered the chamber approximately 20 min after the first pair to prevent cueing at the treadmill walk and stair climb exercise stations and to provide ample time for removal of PADs from one pair of subjects before the second finished their exposure period. Each subject entered the chamber and proceeded to a predetermined exercise station and waited there until instructed to begin testing. Each station was marked with placards to ensure subjects knew where to be in the chamber and which exercises were to be performed at each location. Subjects completed the same 16 activities performed during aerosol test trials; however, the duration for a single activity was 2 min as opposed to one. The metronome was again used for pacing exercises as described for AROM test trials.

At the conclusion of the 32-min challenge period, a subject pair exited the chamber and entered into the first airlock of the clean room area. Each pair waited in this airlock for 4 min and then entered a second airlock room where they waited for an additional 4 min. Each airlock contained a wall timer that was set by a subject. The timers had an audible ring like a kitchen timer that alerted subjects when to move to the next staging area. From the second airlock, subjects entered a doffing room and carefully removed all IPE test items. Subjects were instructed to move deliberately when doffing the equipment and to avoid touching any of the PADs on the head, face and neck. Once all IPE items were removed, subjects proceeded to the clean room where the PADs were removed by a test administrator. Immediately upon removal, each PAD was wrapped in foil and placed into an individually labeled glass vial that was sealed and stored for subsequent analysis. Three background PADs were placed inside the clean room during sampler placement and removal from the subjects and exposure time was recorded.

The IPE test conditions assessed in this phase of testing were identical to those presented in Table 1 with the exception of the Control and Mask conditions. Presentation of conditions was randomly assigned and volunteers were exposed to only one test condition on any given day. Test days were separated by at least 24 hr to allow for MeS off-gassing from IPE test items.

3. RESULTS

3.1 AROM with IPE

3.1.1 AROM of the Cervical Spine for Simple Head Motions

Results for cervical AROM data for simple head movements (i.e., along a single axis) are presented in Figures 3 through 7. The data are expressed as mean ± standard deviation (SD). AROM data represent maximal angles of joint movement from the neutral (zero) position as recorded during digitization of the nine AROM sensors. Unintended displacement of AROM sensors and subject availability for testing resulted in differences in the number of data points analyzed for each IPE test condition.

The largest reduction in leftward cervical rotation during the Head S2S activity was found for the Armor+collar IPE condition, which was significantly less compared to all IPE conditions except the Armor concept (Figure 3). Compared to Control, cervical rotation to the right was reduced for all conditions but the Mask. Helmet, Helmet+weight, Armor, and Armor+collar IPE conditions also differed from the Mask condition. Cervical rotation to the right was also impacted the most for the Armor+collar concept.

For the Head Nod activity, head extension was reduced significantly for the Armor+collar condition compared to Control, Mask, Helmet, and Helmet+weight conditions, but no other differences were observed among the other conditions (Figure 4). The Armor+collar condition also had a significant impact on head flexion compared to all other IPE conditions. Head flexion was also reduced significantly for the Helmet and Armor conditions compared to Control.

Left lateral flexion of the head was not significantly different among the IPE test conditions with the lone exception being a significant reduction in AROM with the Armor+collar condition compared to Control (Figure 5). The Helmet, Helmet+weight, and Armor+collar IPE concepts significantly reduced right lateral flexion of the head compared to Control. Wearing the Armor with the collar also lowered AROM significantly compared to the Mask wear condition.

In addition to the Head S2S movements, cervical rotation was assessed during the H&K-Head S2S and Traffic AROM activities. For the H&K-Head S2S exercise, cervical rotation was not impacted for the Mask only condition, but was reduced significantly compared to Control and Mask beginning with the Suit condition and all other IPE conditions in the left and right directions (Figure 6). As with Head S2S in the standing position, the Armor+collar concept limited AROM the most. However, in this instance, the decrement in rightward rotation was greater than that observed for rotation to the left. In contrast, cervical rotation to the right during the Traffic exercise did not differ significantly among IPE test conditions, but leftward rotation was significantly reduced for the Helmet+weight, Armor, and Armor+collar conditions compared to both Control and Mask (Figure 7).

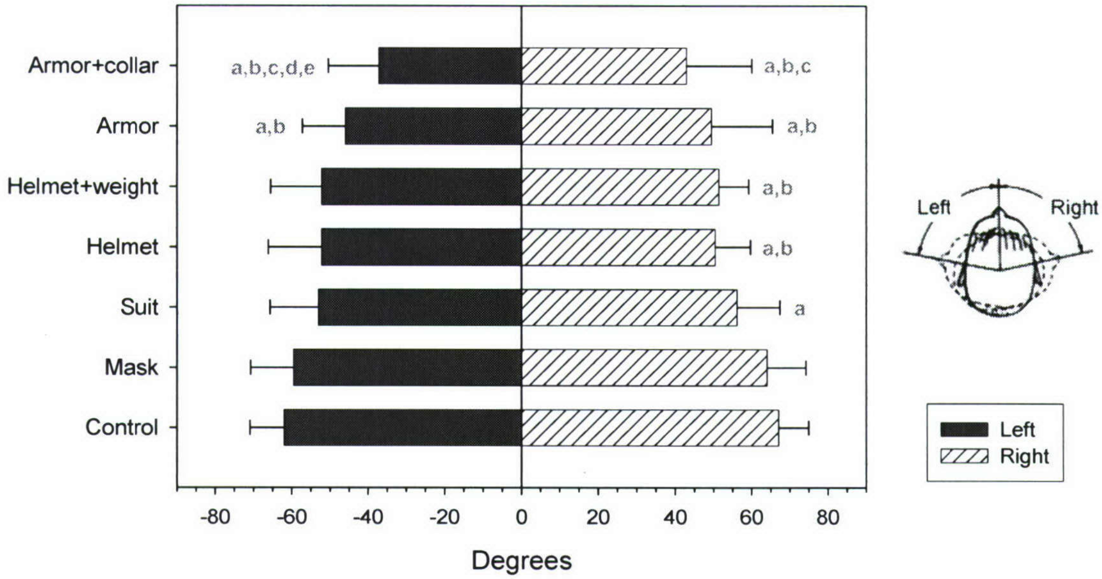


Figure 3. AROM for Cervical Rotation during the Head S2S Activity for each IPE Condition. Letters identify significant ($p<0.05$) differences among conditions according to the following: a=different vs. Control, b=different vs. Mask, c=different vs. Suit, d=different vs. Helmet, e=different vs. Helmet+weight, and f=different vs. Armor.

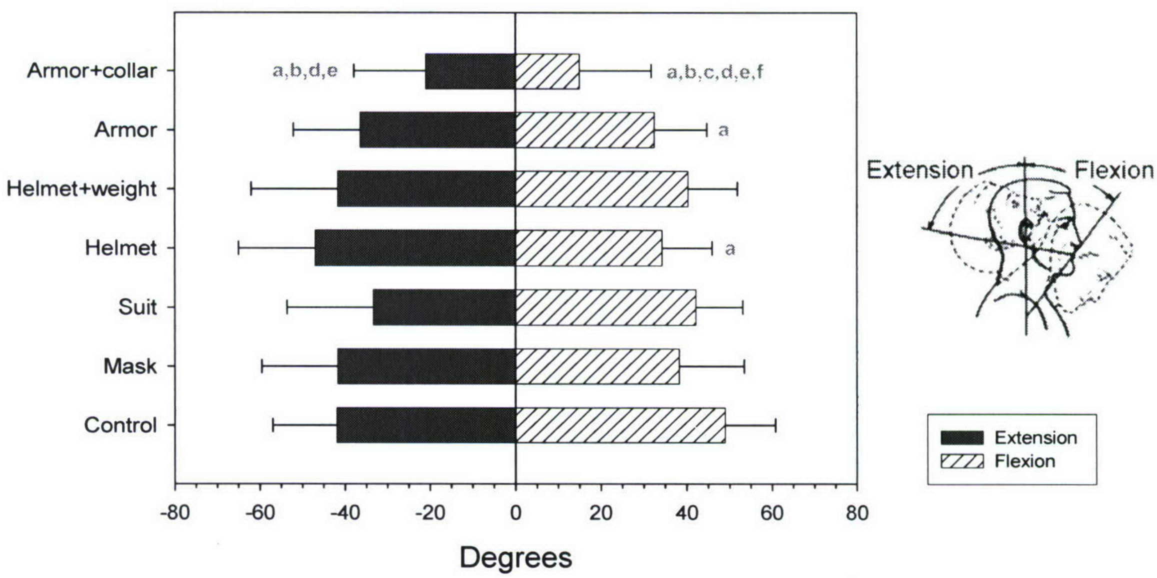


Figure 4. AROM for Cervical Flexion and Extension during the Head Nod Activity. See Figure 3 for definitions of the letters used for identifying differences among conditions.

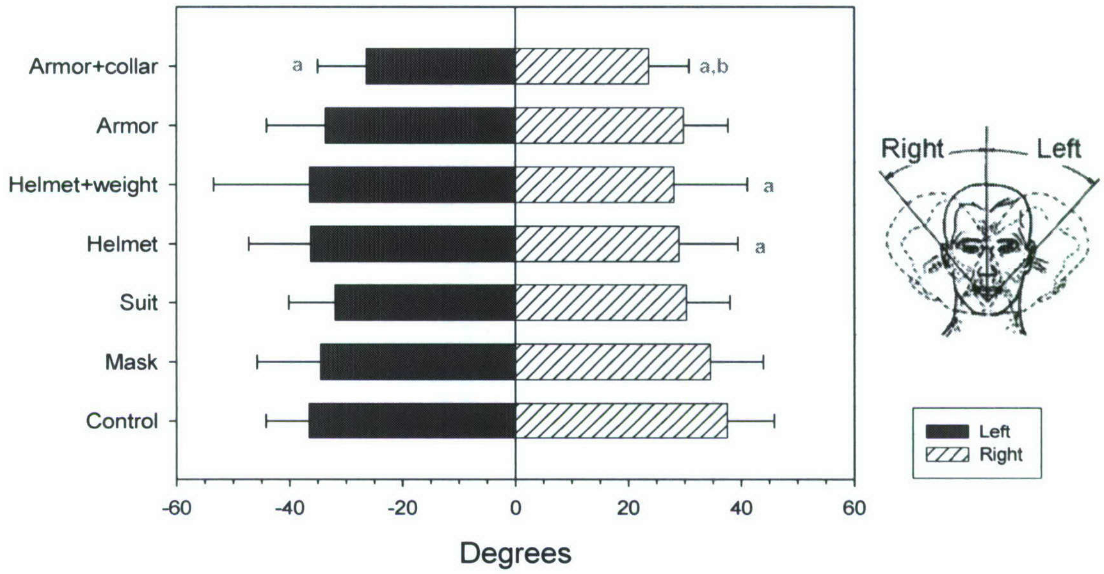


Figure 5. AROM for Cervical Right and Left Lateral Flexion for the Head Lat Flex Activity. See Figure 3 for definitions of the letters used for identifying differences among conditions.

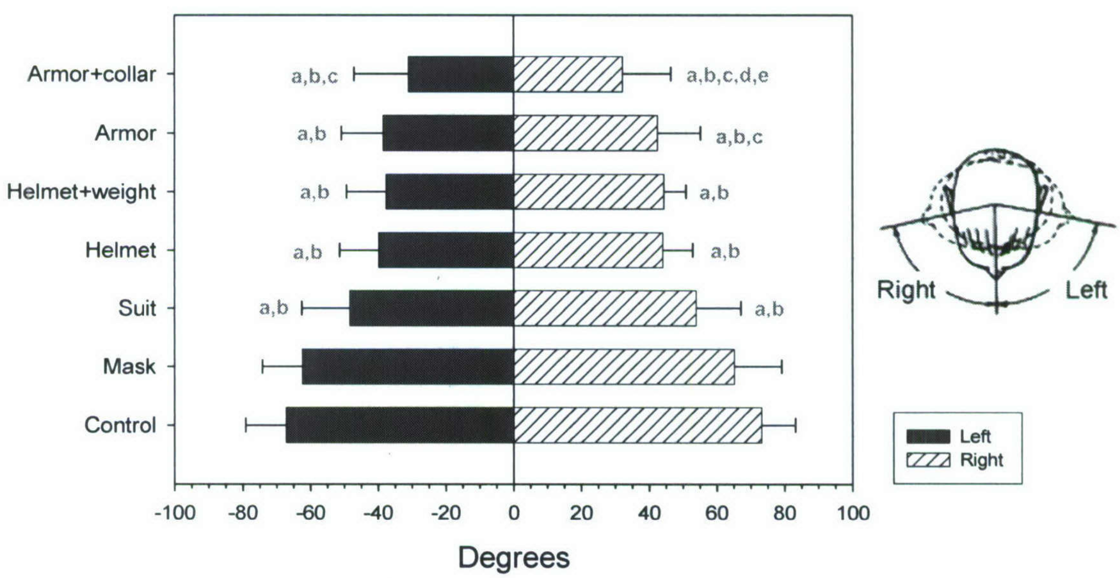


Figure 6. Cervical AROM during H&K-Head S2S Movements. Reference Figure 3 for definitions of the letters used for identifying differences among conditions.

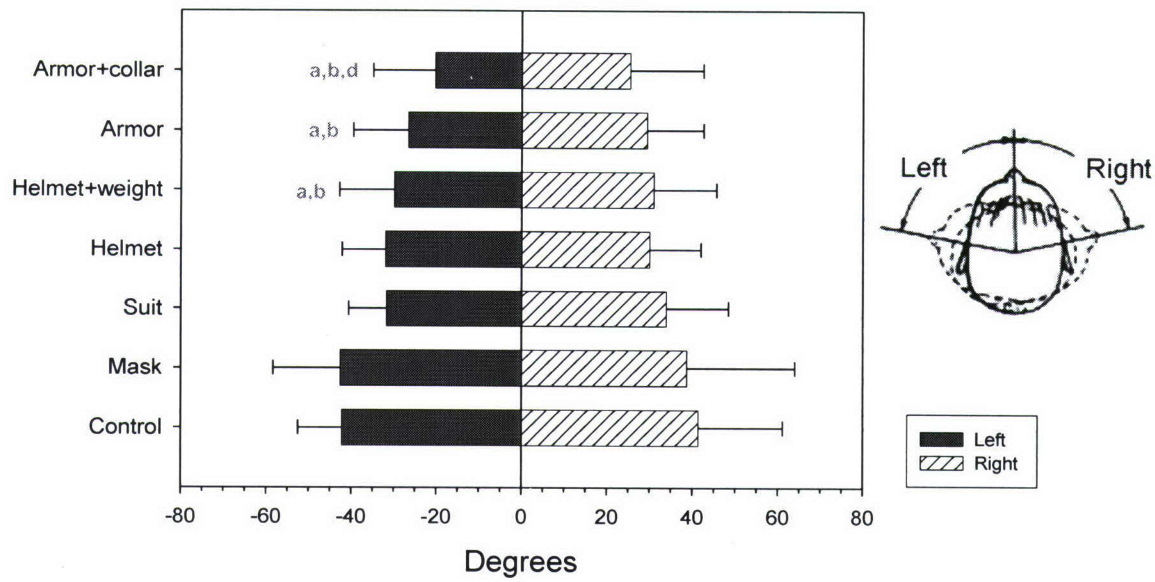


Figure 7. Left and Right Cervical Rotation during Traffic Movements. See Figure 3 for definitions of the letters used for identifying differences among conditions.

Total head AROM data representing the full range of movement about the cervical axis are presented in Table 4. In general, the most substantial reductions in total head movements were for the Armor+collar IPE configuration. Likewise, all AROM activities that involved cervical rotation showed significant reductions in total AROM for almost all conditions compared to the Control and Mask concepts.

AROM PR results for total range of movement for cervical flexion and extension showed decrements in performance of roughly 10% or less for all IPE conditions, except the Armor and Armor+collar concepts, compared to Control (Table 5). Average performance decrement with the Armor+collar condition was over 50% (AROM PR = 47%). No significant performance decrements were found among IPE conditions for total lateral head flexion other than for the Armor+collar condition, which had an average AROM PR of 72%. Performance decrements in cervical rotation for all head rotation activities varied considerably, particularly for the Head S2S and Traffic AROM exercises. However, significant performance reductions were evident only for the Armor+collar condition compared to the Mask condition for these exercises. Average AROM PR data for head rotation for the H&K-Head S2S activity indicated a significant decrement in head rotation with wear of the CB protective suit. Average performance decrement with the Armor+collar condition was over 50% (AROM PR = 49%) for this activity.

3.1.2 AROM for Simple Body Motions

Results for AROM data for simple body movements of Twist and Arms Up are presented in Figures 8 through 10 and in Table 5. Thoracic rotation during the Twist activity differed little among the IPE test conditions in either direction with the following exceptions: rotation to the left was significantly less for the Helmet+weight condition versus Control and rightward rotation under Armor conditions differed significantly from the Control and Mask conditions (Figure 8).

Table 4. Average Total AROM (± SD) of Select Head Movements for Each IPE Condition

Condition	N	Flexion & extension (°)	Lateral Flexion (°)	Rotation (°)	Hands&Knees – Rotation (°)	Traffic – Rotation (°)
Control	27	90.9 ± 14.1	74.1 ± 10.7	129.0 ± 14.2	140.4 ± 19.6	84.8 ± 16.1
Mask	21	80.0 ± 16.0	69.1 ± 13.7	123.5 ± 15.7	127.5 ± 15.7	82.3 ± 17.7
Suit	24	75.5 ± 16.5^{a}	62.3 ± 14.3^{a}	109.2 ± 21.9^{a}	$102.3 \pm 24.6^{a,b}$	65.7 ± 19.0^{a}
Helmet	25	81.3 ± 18.1	65.3 ± 11.4	$102.5 \pm 18.4^{a,b}$	$83.9 \pm 16.1^{a,b,c}$	$62.0 \pm 16.6^{a,b}$
Helmet+weight	18	82.1 ± 16.7	64.5 ± 10.5	$103.5 \pm 17.7^{a,b}$	$82.0 \pm 13.3^{a,b,c}$	$61.1 \pm 17.6^{a,b}$
Armor	18	68.9 ± 9.1^{a}	63.4 ± 11.7	$95.4 \pm 21.6^{a,b}$	$81.1 \pm 17.8^{a,b,c}$	$56.0 \pm 22.4^{a,b}$
Armor+collar	18	$41.3 \pm 10.2^{a,b,c,d,e,f}$	$50.0 \pm 10.7^{a,b,c,d,e,f}$	$80.1 \pm 26.1^{a,b,c,d,e}$	$63.2 \pm 25.2^{a,b,c,d}$	$45.7 \pm 25.7^{a,b,c}$

[a] = significantly different from Control
[b] = significantly different from Mask
[c] = significantly different from Suit
[d] = significantly different from Helmet
[e] = significantly different from Helmet+weight
[f] = significantly different from Armor

Table 5. Average Total AROM PR (± SD) of Select Head Movements for Each IPE Condition

Condition	N	Flexion & extension (%)	Lateral Flexion (%)	Rotation (%)	Hands&Knees – Rotation (%)	Traffic – Rotation (%)
Mask	21	91 ± 15	96 ± 13	106 ± 21	95 ± 6	111 ± 44
Suit	24	83 ± 12	85 ± 17	91 ± 24	75 ± 16^{b}	87 ± 30
Helmet	25	89 ± 15	89 ± 18	87 ± 32	$61 \pm 11^{b,c}$	81 ± 31
Helmet+weight	18	94 ± 12	93 ± 21	93 ± 33	64 ± 14^{b}	88 ± 36
Armor	18	79 ± 9^{e}	91 ± 19	87 ± 35	63 ± 16^{b}	81 ± 41
Armor+collar	18	$47 \pm 12^{b,c,d,e,f}$	$72 \pm 14^{b,d,e,f}$	72 ± 35^{b}	$49 \pm 20^{b,c,e}$	64 ± 38^{b}

[a] = significantly different from Control
[b] = significantly different from Mask
[d] = significantly different from Helmet
[c] = significantly different from Suit
[e] = significantly different from Helmet+weight
[f] = significantly different from Armor

Total thoracic rotation (i.e., complete rotation from left to right) was reduced for all IPE conditions involving wear of the CB protective suit (Figure 9). Compared to Control, significant differences were observed for the Suit, Helmet+weight, Armor, and Armor+collar conditions. Thoracic AROM also differed significantly for the Helmet+weight, Armor, and Armor+collar concepts compare to the Mask condition.

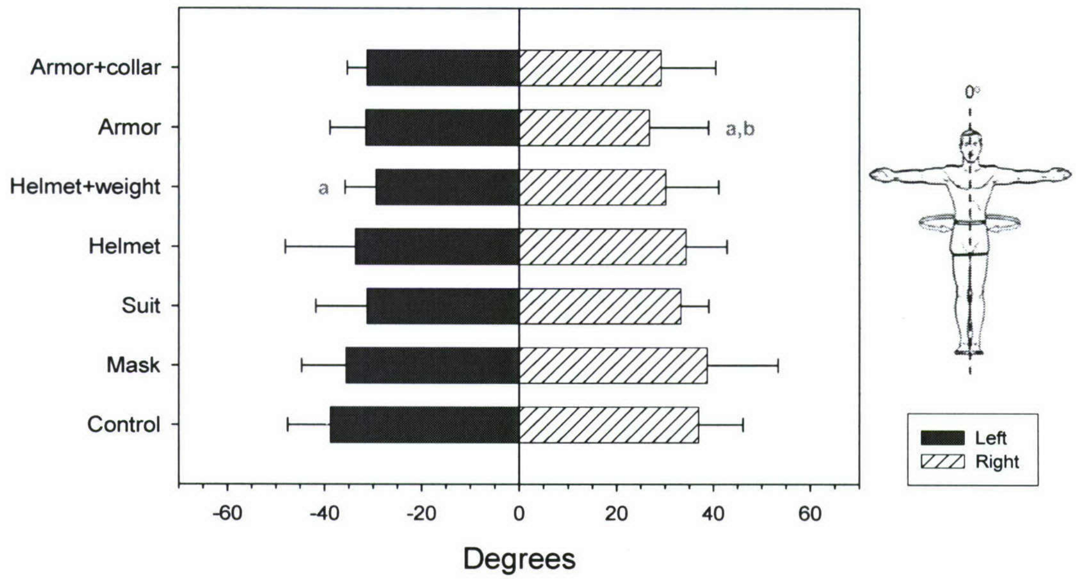


Figure 8 Left and Right Thoracic Rotation for the Twist AROM Activity. See Figure 3 for definitions of the letters used for identifying differences among conditions.

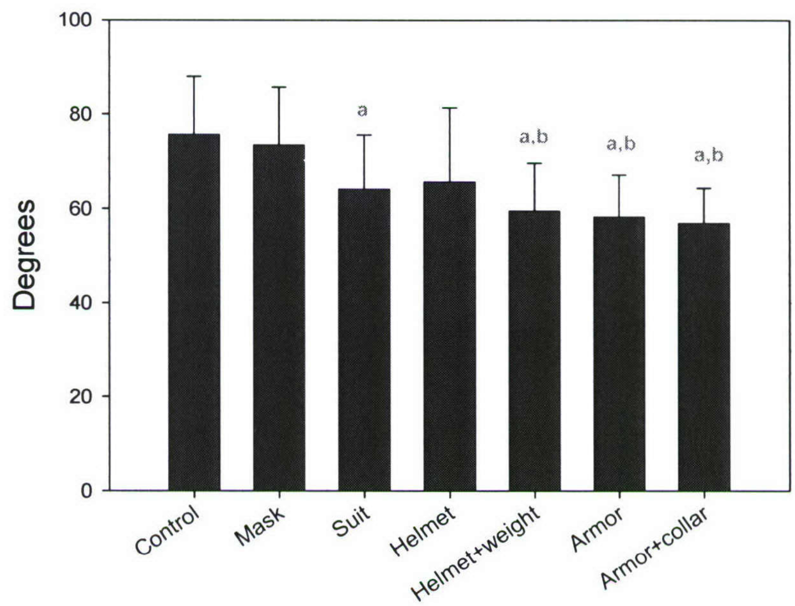


Figure 9. Total Thoracic Rotation during the Twist AROM Exercise. See Figure 3 for definitions of the letters used for identifying differences among conditions.

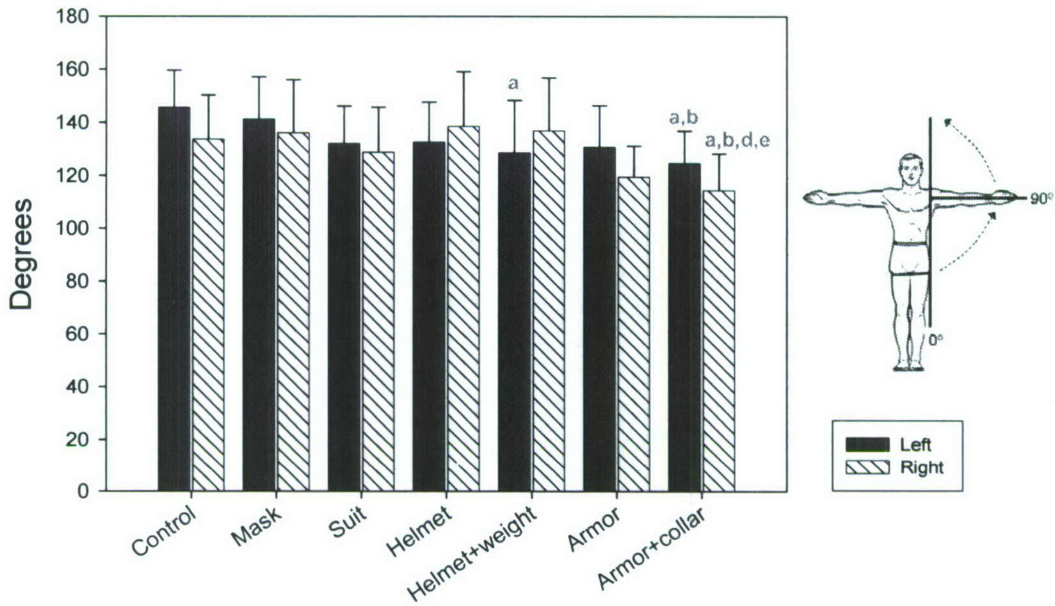


Figure 10. Left and Right Shoulder Abduction. See Figure 3 for definitions of the letters used for identifying differences among conditions.

Few differences among IPE conditions were evident for left and right shoulder abduction measured during the Arms Up activity. For the left shoulder, abduction was significantly less for the Helmet+weight and Armor+collar conditions compared to Control and for the Armor+collar concept versus Mask conditions (Figure 9). Right shoulder abduction was lowest for the Armor+collar condition, which differed significantly from all others but the Suit and Armor conditions.

Table 6. Average AROM PR (± SD) for the Twist and Arms Up Activities

Condition	N	Twist: Total thoracic rotation (%)	Arms Up: Shoulder abduction (%)
Mask	21	91 ± 15	96 ± 13
Suit	24	83 ± 12	85 ± 17
Helmet	25	89 ± 15	89 ± 18
Helmet+weight	18	94 ± 12	93 ± 21
Armor	18	79 ± 9[e]	91 ± 19
Armor+collar	18	47 ± 12[b,c,d,e,f]	72 ± 14[b,d,e,f]

[a] = *significantly different from Control*
[b] = *significantly different from Mask*
[c] = *significantly different from Suit*
[d] = *significantly different from Helmet*
[e] = *significantly different from Helmet+weight*
[f] = *significantly different from Armor*

Average AROM PR results for total thoracic rotation during the Twist activity and shoulder abduction for the Arms Up exercise are presented in Table 6. The decrement in thoracic rotation performance evident for the Armor+collar condition (>50%) was significantly different from all other IPE concepts. The Armor+collar condition also resulted in the lowest AROM PR values for shoulder abduction during the Arms Up exercise, which differed significantly from all conditions other than the Suit.

3.1.3 AROM for Complex Body Motions

Body movements associated with the activities Sit, Bend & Reach, Rifle, Pistol, Lunge and Step were categorized as complex motions because several joints were moved to perform the AROM activities. As such, multiple joint angles were assessed. Even though the Traffic and H&K-Head S2S AROM activities also necessitated multiple joint movements, they were not considered as complex motions for this analysis because the head motions performed for these were of primary interest.

The motions analyzed for the Bend & Reach AROM exercise were thoracic flexion, left and right hip flexion, and left and right shoulder flexion (Table 7). Thoracic flexion was reduced for all conditions of chemical suit wear compared to the non-suit conditions (i.e., Control and Mask). Reductions in thoracic flexion were significant for the Helmet+weight, Armor, and Armor+collar concepts versus the Control and Mask conditions. Left and right hip flexion were also reduced for the chemical suit wear conditions compared to the non-suit conditions and the differences between the Suit and Mask and Armor+collar and Mask conditions were significant. With the exception of the difference between Helmet and Armor+collar, left and right shoulder flexion did not differ among the IPE test conditions.

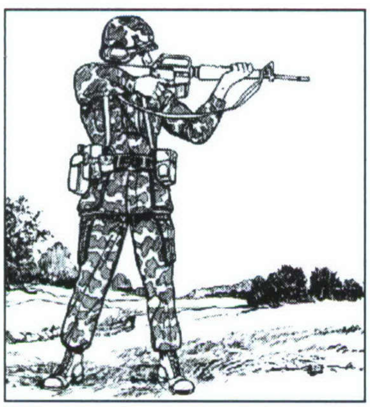
Table 7. Average (± SD; (*N*)) AROM for Thoracic, Hip, and Shoulder Flexion during the Bend and Reach Activity Based on IPE Condition

Condition	Thoracic Flexion (^{o})	Hip Flexion (^{o})		Shoulder Flexion (^{o})	
		Left	Right	Left	Right
Control	60.3 ± 20.8 (24)	86.3 ± 18.9 (27)	84.1 ± 17.3 (27)	146.0 ± 16.5 (27)	146.9 ± 19.2 (27)
Mask	60.7 ± 23.3 (21)	92.6 ± 17.2 (21)	89.7 ± 16.5 (21)	145.6 ± 16.4 (21)	146.2 ± 19.2 (21)
Suit	47.3 ± 15.5 (24)	75.1 ± 15.9[b] (24)	70.7 ± 20.2[b] (24)	146.5 ± 9.9 (24)	146.4 ± 16.6 (24)
Helmet	45.5 ± 16.2 (22)	78.8 ± 23.9 (25)	74.9 ± 22.1 (25)	150.9 ± 11.2 (25)	143.9 ± 12.9 (24)
Helmet+weight	38.6 ± 5.3[a,b] (18)	77.1 ± 21.7 (18)	75.8 ± 20.5 (18)	139.5 ± 20.9 (18)	144.1 ± 16.4 (18)
Armor	40.1 ± 11.9[a,b] (18)	74.4 ± 14.3 (18)	73.1 ± 14.4 (18)	137.8 ± 13.2 (18)	137.4 ± 12.3 (18)
Armor+collar	42.8 ± 16.1[a,b] (18)	70.8 ± 16.7[b] (18)	67.6 ± 17.3[b] (18)	136.4 ± 12.5 (18)	140.3 ± 14.0[d] (18)

[a] = *significantly different from Control*
[b] = *significantly different from Mask*
[c] = *significantly different from Suit*
[d] = *significantly different from Helmet*
[e] = *significantly different from Helmet+weight*
[f] = *significantly different from Armor*

No significant differences among test conditions were observed for Bend & Reach AROM PR values calculated for left and right hip flexion and left and right shoulder flexion. Average thoracic flexion AROM PR results for the Suit (87%), Helmet (71%), Helmet+weight (70%), and Armor (71%) all differed significantly from the Mask condition (97%). However, AROM PR values did not reach significance (p=0.09) for the comparison between the Armor+collar (77%) and Mask conditions. No other differences were found among the remaining conditions.

All subjects performed the Rifle AROM activity right-handed. As such, the right hand was positioned on the pistol grip and the left hand was on the upper handguard while the subject assumed a standing firing position by facing a forward target and spreading the feet a comfortable distance apart. With both hands positioned on the rifle, the butt of the rifle was placed in the pocket formed by the firing shoulder so the sights were level with their eyes (Figure 11). The joint motions analyzed from this position were cervical flexion, right lateral cervical flexion, leftward cervical rotation, and right shoulder abduction. No significant differences in cervical flexion or cervical right lateral flexion were observed among IPE conditions (Table 8). Cervical rotation to the left was reduced significantly for the Helmet+weight and Armor+collar conditions compared to the Mask condition, but no other differences among the remaining IPE concepts were found. Finally, shoulder abduction results varied considerably among test participants as witnessed by the large variance in the data. However, no significant differences in average shoulder abduction values were observed among the test conditions.



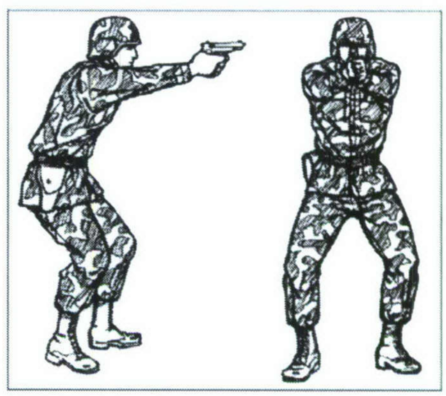


Figure 11. Depictions of the Stances Used for the Rifle (left) and Pistol (right) AROM Exercises

Due to the large variance in the data among conditions, no significant differences were observed for Rifle AROM PR values calculated for cervical flexion, right lateral cervical flexion, and shoulder abduction motions. Average leftward cervical rotation AROM PR results for the Mask condition (119%) suggest that subjects rotated their head further to the left for sighting the rifle during mask wear. Average AROM PR data for the Suit (95%), Helmet (93%), Helmet+weight (89%), Armor (87%) and Armor+collar (70%) all differed significantly from the Mask condition, but only the difference between the Armor+collar and Mask conditions was significant.

Table 8. Average (± SD; (*N*)) AROM for Joint Angles Assessed during the Rifle Activity Based on IPE Condition

Condition	Cervical Flexion (°)	Cervical Right Lateral Flexion (°)	Cervical Leftward Rotation (°)	Right Shoulder Abduction (°)
Control	24.2 ± 13.1 (27)	17.6 ± 9.8 (26)	34.5 ± 13.3 (27)	61.9 ± 51.3 (27)
Mask	24.5 ± 19.0 (23)	22.1 ± 9.1 (22)	40.5 ± 17.4 (24)	60.5 ± 44.7 (25)
Suit	23.4 ± 6.7 (20)	20.0 ± 7.3 (20)	32.1 ± 14.5 (20)	65.4 ± 27.2 (20)
Helmet	20.1 ± 12.5 (25)	20.6 ± 12.0 (25)	31.8 ± 15.2 (25)	75.3 ± 36.3 (25)
Helmet+weight	23.3 ± 9.4 (18)	24.6 ± 15.6 (18)	25.4 ± 7.7[b] (18)	53.5 ± 28.1 (18)
Armor	23.9 ± 18.4 (18)	21.8 ± 9.2 (18)	27.4 ± 11.9 (18)	67.4 ± 28.8 (18)
Armor+collar	15.4 ± 20.2 (18)	21.5 ± 9.9 (18)	23.3 ± 12.0[b] (18)	70.1 ± 22.0 (18)

[a] = *significantly different from Control*
[b] = *significantly different from Mask*
[c] = *significantly different from Suit*
[d] = *significantly different from Helmet*
[e] = *significantly different from Helmet+weight*
[f] = *significantly different from Armor*

As with the Rifle AROM activity, all subjects performed the Pistol AROM activity right-handed. In brief, the simulated pistol AROM exercise included removal of the mock pistol from a holster with the firing hand, raising the firing arm to a pistol ready position with the upper arm close to the body and the forearm at about a 45° angle, and placing the body in a forward crouch with the knees bent slightly and trunk bent forward from the hips and the feet in a position to allow a step toward a target. Subjects then extended the firing arm, attained a two hand grip on the pistol, extended the weapon straight toward the target, and locked the wrist and elbow of the firing arm (Figure 11). The joint motions analyzed from this position were shoulder flexion and internal rotation. No significant differences in left shoulder flexion and internal rotation or right shoulder internal rotation were observed among IPE conditions. However, right shoulder flexion was significantly less for the Armor and Armor+collar conditions compared to all other IPE concepts (Figure 12). These findings were reflected in AROM PR values that showed little to no decrement in right shoulder flexion for the Mask (PR = 98%), Suit (PR =100%), Helmet (PR = 98%), and Helmet+weight (PR = 100%) conditions, with larger decrements for the Armor (PR = 87%) and Armor+collar (PR = 88%) concepts. Average AROM PR for the Armor and Armor+collar conditions differed significantly from all other IPE conditions.

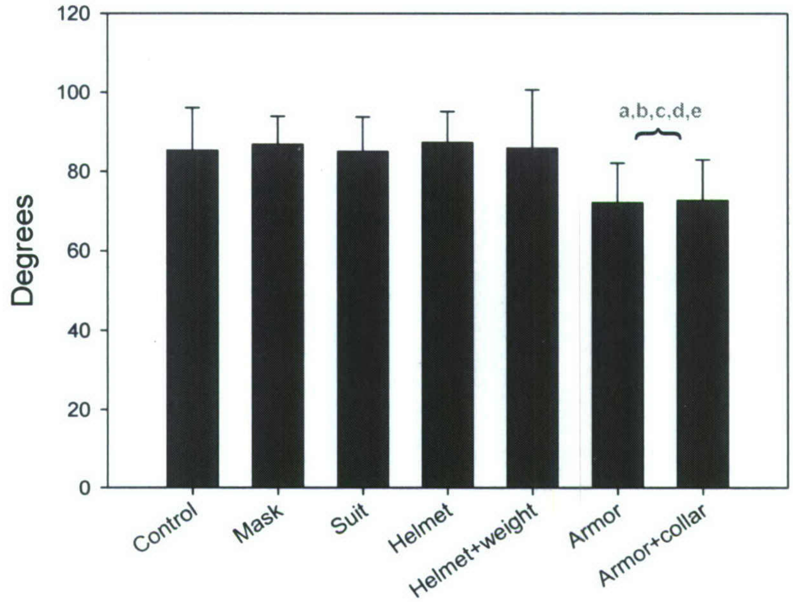


Figure 12. Right Shoulder Flexion for the Pistol AROM Activity. See Figure 3 for definitions of the letters used for identifying differences among conditions.

Hip flexion recorded for the Sit AROM exercise was relatively similar among IPE test conditions, however flexion of the right and left hip was significantly less for the Helmet condition compared to the Control, Armor, Armor+collar conditions (Figure 13). Average hip AROM PR data showed no substantial decrements in performance for the all conditions other than the Helmet (left hip AROM PR = 86%; right hip AROM PR = 83%). Results for both hips differed significantly for the Armor (left hip AROM PR = 110%; right hip AROM PR = 108%) and Armor+collar (left hip AROM PR = 110%; right hip AROM PR = 105%) conditions compared to the Helmet concept.

Left hip flexion during the Lunge activity was similar among all test conditions (Figure 14). Right hip flexion was significantly less for the Suit, Helmet, Helmet+weight, and Armor+collar conditions compared to control. The Helmet+weight concept also differed from the Mask condition for right hip flexion for the Lunge AROM exercise (Figure 14). Average left hip AROM PR results were above 90% for all conditions and no significant differences were found among conditions. However, right hip AROM PR results ranged from a low 80% for the Helmet+weight condition to a high of 95% for the Mask concept during the Lunge activity. Right hip AROM PR results for the Helmet (83%) and Helmet+weight (80%) conditions were significantly less than the Mask results.

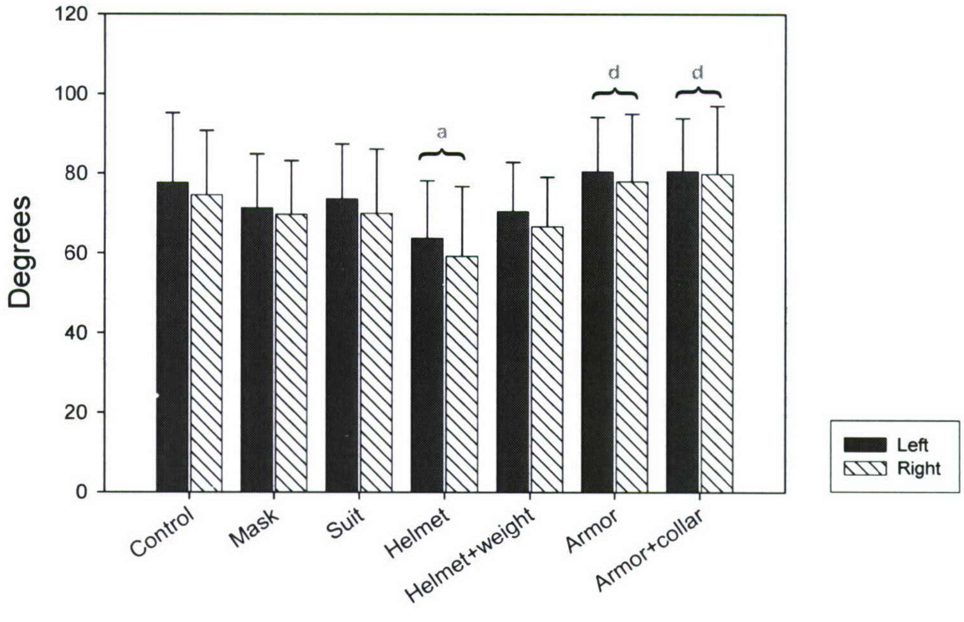


Figure 13. Hip Flexion during the Sit AROM Activity. See Figure 3 for definitions of the letters used for identifying differences among conditions.

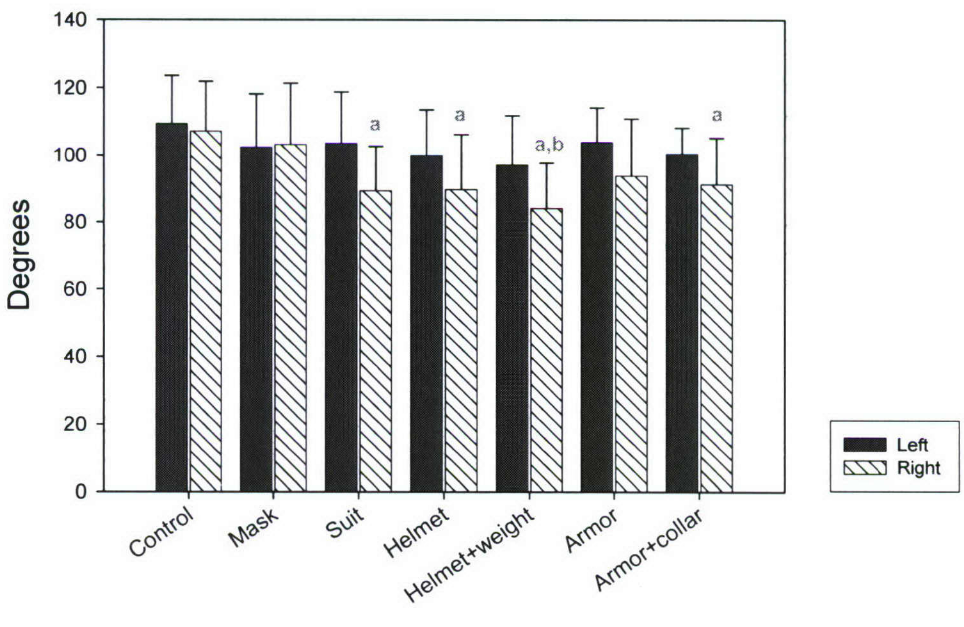


Figure 14. Hip Flexion during the Lunge AROM Exercise. See Figure 3 for definitions of the letters used for identifying differences among conditions.

Results for right and left knee flexion during the Lunge and Step AROM activities are presented in Table 9. No differences in knee flexion were observed among conditions during lunging. Likewise, performance rating results for knee flexion during lunging showed relatively minor decrements in performance (PR ≥ 96%) for both knees and no differences were found among conditions.

For the Step AROM activity, right knee flexion was significantly higher for the Armor and Armor+collar conditions compared to all others except the Helmet concept. Left knee flexion was generally the same among IPE conditions, but a significant difference was found between Armor and Helmet conditions. Average AROM PR results for both the left and right knees were equal to or slightly higher than 100%, indicating that no decrements in knee flexion while stepping were evident due to the IPE conditions.

Table 9. Average (± SD; (*N*)) AROM for the Left and Right Knee Joints during the Lunge and Step Activities Based on IPE Condition

	Lunge Activity		Step Activity	
Condition	Left Knee Flexion (°)	Right Knee Flexion (°)	Left Knee Flexion (°)	Right Knee Flexion (°)
Control	99.3 ± 13.0 (25)	97.7 ± 14.2 (25)	86.7 ± 12.2 (25)	87.3 ± 10.3 (25)
Mask	98.6 ± 13.3 (21)	97.4 ± 16.2 (21)	86.2 ± 8.5 (21)	86.9 ± 9.0 (21)
Suit	92.3 ± 15.8 (19)	93.2 ± 11.5 (19)	88.8 ± 10.9 (22)	86.3 ± 5.8 (22)
Helmet	94.4 ± 15.6 (22)	95.0 ± 13.3 (22)	89.9 ± 11.0 (23)	90.8 ± 8.8 (23)
Helmet+weight	93.8 ± 14.9 (18)	95.9 ± 10.6 (18)	84.3 ± 9.2 (18)	86.4 ± 4.8 (18)
Armor	104.8 ± 12.8 (15)	105.5 ± 15.0 (15)	96.7 ± 10.3[e] (15)	95.6 ± 2.8[a,b,c,e] (15)
Armor+collar	103.7 ± 13.2 (15)	104.9 ± 17.5 (15)	92.6 ± 7.6 (15)	95.5 ± 4.3[a,b,c,e] (15)

[a] = *significantly different from Control*
[b] = *significantly different from Mask*
[c] = *significantly different from Suit*
[d] = *significantly different from Helmet*
[e] = *significantly different from Helmet+weight*
[f] = *significantly different from Armor*

3.2 Respiratory Protection from Aerosols

Aerosol PF (PF-A) data were analyzed to determine changes in protection based on the addition of specific IPE items. Two test subjects were asked to repeat Mask trials based on circumspect results from their initial tests. Data from the repeated tests were substituted for initial Mask trials for these subjects in the final analysis.

No significant differences in average PF-A were found among test conditions during any of the exercises performed in the aerosol chamber with the exception of the Head S2S and H&K-Head S2S activities. Respirator PF-A during the Head S2S movements were significantly less for the Armor+collar condition compared to the Suit, Helmet, and Armor concepts (Figure 15). However, average PF-A exceeded the NIOSH requirement for CBRN APR of 2000 (Log_{10} PF = 3.3) for this exercise. During H&K-Head S2S activities, wear of the

Armor+collar concept decreased respirator PF-A significantly compared to all other IPE conditions (Figure 16). Average PF-A for the Armor+collar condition only just exceeded the NIOSH requirement (PF = 2138; Log_{10} PF = 3.33). Despite the differences observed for the Head S2S and H&K-Head S2S activities, overall respirator PF-A were statistically similar among all IPE conditions independent of the exercise motions (Figure 17).

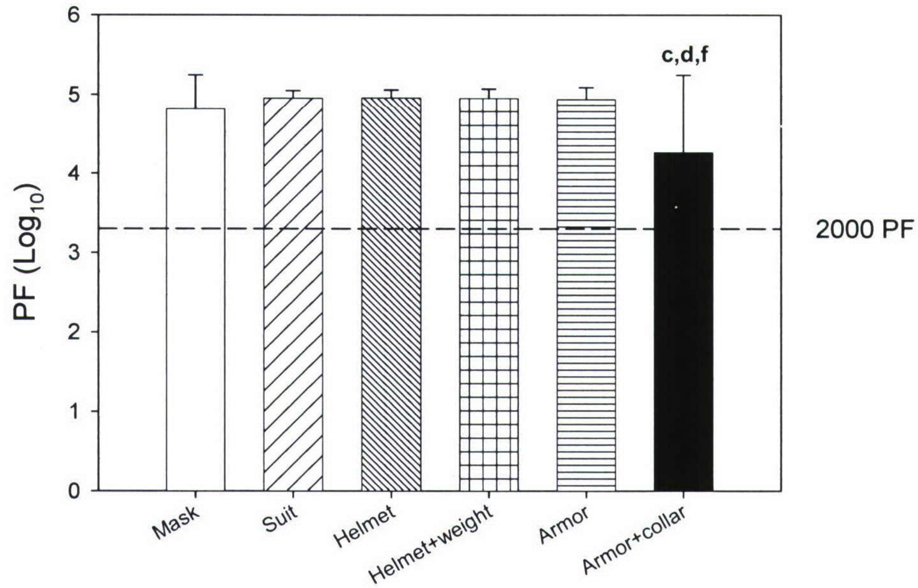


Figure 15. Respirator PFs during Head S2S Movements. See Figure 3 for definitions of the letters used for identifying differences among conditions.

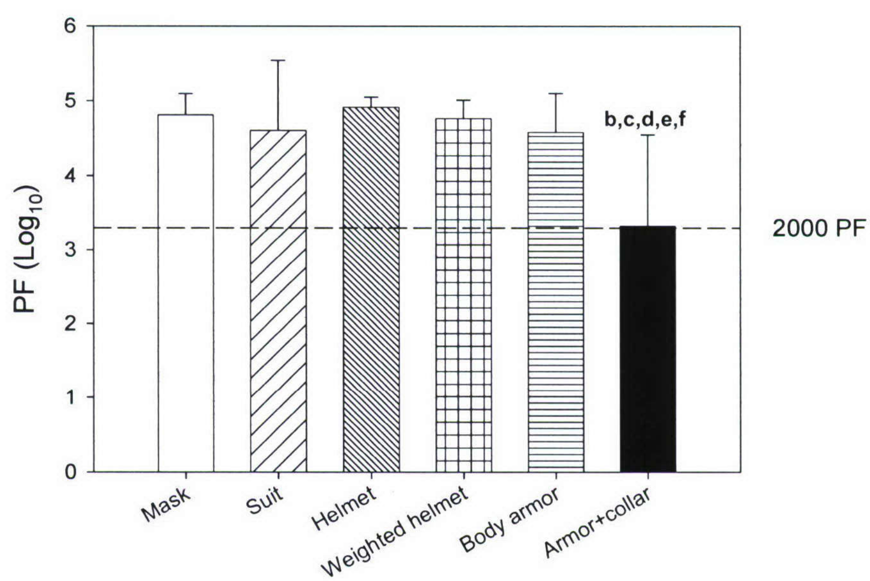


Figure 16. Average Respirator PFs during H&K-Head S2S Movements. See Figure 3 for definitions of the letters used for identifying differences among conditions.

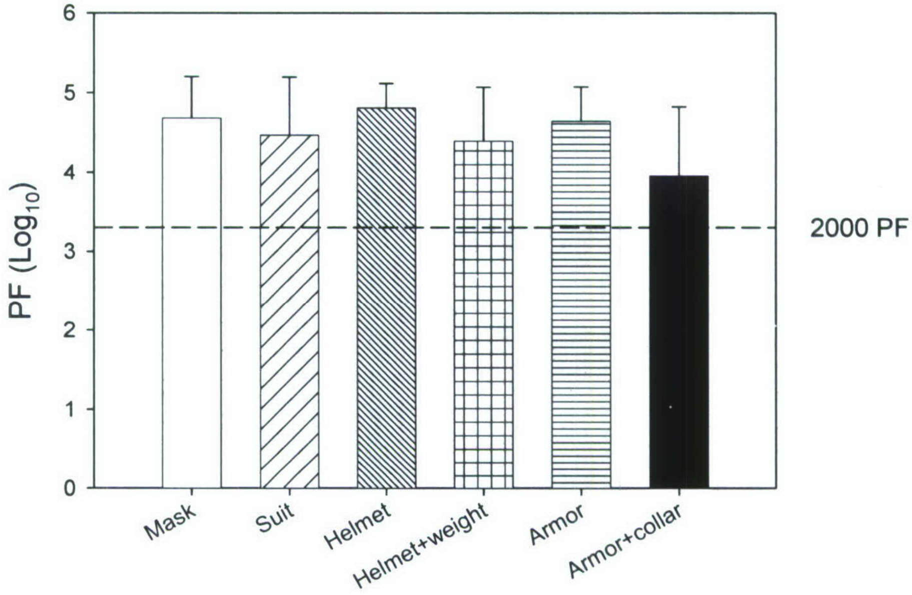


Figure 17. Average Respirator PFs for Each IPE Condition Independent of Exercise Activity

3.3 Estimates of Head, Face, and Neck Protection from Gases and Vapors

Each IPE configuration was worn by a total of four test participants over the course of six trials. During the initial trial the forehead PAD was placed on the forehead under the hood of the suit but outside of the mask. To obtain an additional in mask data point this PAD was moved inside of the mask's peripheral seal for all subsequent trials. Three of the four participants repeated the first trial with the forehead PAD inside of the mask. The forehead PAD data presented herein reflects MeS penetration within the mask seal.

3.3.1 MeS Penetration

The target dosage of MeS for these trials was 3,200 mg·min/m^3, which correlates to a 100 mg/m^3 challenge for 32 min. The total MeS dosage measured during each of the chamber exposure trials averaged 3,308 mg·min/m^3, for an average challenge of 103.4 mg/m^3 for 32 min. The mass of the MeS absorbed by the PADs for each trial was determined using GC analysis. The MeS background concentrations obtained from the three PADs used for each subject pair were averaged for each trial and subtracted from each head, neck, and face PAD. The mass of each test subject's sample PADs was then normalized to the target dosage according to the equation

$$Normalized\ Mass\ (ng) = [Sample\ PAD\ (ng) - Background\ \ Average\ (ng)] * \left(\frac{TargetDose}{ActualDose}\right) \quad (2)$$

A few PAD samplers were dislodged or lost in the course of testing, during the transfer of the Tenax TA to the sorbent tube after testing, or in the analysis process.

Several PADs were found to have MeS accumulation values below 10 ng, the lower detection limit of the analysis equipment. These were marked as below detection limit (BDL) samples and were assigned normalized mass values of 10 ng for calculations of PAD protection factors. The normalized masses for each PAD for each subject are presented in Tables 10 through 13 and average MeS mass penetrations for all IPE conditions are listed in Table 14.

Table 10. Normalized PAD Mass by IPE Condition for Test Participant 1

PAD ID	PAD Location	Suit (ng)	Helmet (ng)	Helmet+weight (ng)	Armor (ng)	Armor+collar (ng)
1	Scalp	178.2	BDL	BDL	97.1	⊗
1A	Forehead	BDL	BDL	BDL	206.7	BDL
2	Behind Left Ear Up	994.6	15.0	BDL	BDL	BDL
3	Behind Left Ear	5,677.8	BDL	251.0	3,084.1	1,717.2
4	Neck Right	20,704.1	13,282.8	18,625.7	14,590.2	10,715.5
5	Neck Left	22,155.9	12,351.3	7,092.9	17,785.6	13,324.0
6	Nape of Neck	6810.1	815.8	134.6	3,371.2	153.2
19	Right Cheek	282.2	BDL	BDL	BDL	BDL
19A	Left Cheek	187.1	74.1	344.4	262.7	63.3

BDL = below detection limit *⊗ = missing PAD*

Table 11. Normalized PAD Mass by IPE Condition for Test Participant 2

PAD ID	PAD Location	Suit (ng)	Helmet (ng)	Helmet+weight (ng)	Armor (ng)	Armor+collar (ng)
1	Scalp	291.3	BDL	416.8	88.1	BDL
1A	Forehead	247.9	BDL	393.2	BDL	BDL
2	Behind Left Ear Up	4,529.7	BDL	1,994.2	274.5	BDL
3	Behind Left Ear	7,783.1	4,274.3	3,941.0	1,137.7	2,813.8
4	Neck Right	9,734.7	9,742.2	11,165.2	5,346.9	8,315.5
5	Neck Left	10,681.5	14,451.5	10,270.9	4,006.3	6,626.8
6	Nape of Neck	5,187.7	3,621.8	4,338.9	1,050.2	2,495.5
19	Right Cheek	BDL	BDL	96.7	BDL	BDL
19A	Left Cheek	76.9	BDL	59.0	51.4	BDL

BDL = below detection limit

Table 12. Normalized PAD Mass by IPE Condition for Test Participant 3

PAD ID	PAD Location	Suit (ng)	Helmet (ng)	Helmet+weight (ng)	Armor (ng)	Armor+collar (ng)
1	Scalp	815.7	BDL	18.8	BDL	BDL
1A	Forehead	BDL	499.0	BDL	BDL	BDL
2	Behind Left Ear Up	4,875.2	109.2	63.7	BDL	152.4
3	Behind Left Ear	7,653.8	485.9	211.8	922.6	618.4
4	Neck Right	13,035.4	⊗	4,678.4	8,786.4	6,900.9
5	Neck Left	14,769.0	12,875.7	7,979.3	BDL	⊗
6	Nape of Neck	5,710.9	3,278.5	1,954.3	1,268.4	3,760.1
19	Right Cheek	BDL	89.5	26.3	BDL	99.2
19A	Left Cheek	BDL	209.9	⊗	BDL	BDL

BDL = below detection limit *⊗ = missing PAD*

Table 13. Normalized PAD Mass by IPE Condition for Test Participant 4

PAD ID	PAD Location	Suit (ng)	Helmet (ng)	Helmet+weight (ng)	Armor (ng)	Armor+collar (ng)
1	Scalp	329.1	BDL	BDL	87.3	133.6
1A	Forehead	56.3	BDL	BDL	NA	1,406.0
2	Behind Left Ear Up	⊗	183.6	508.2	BDL	91.0
3	Behind Left Ear	⊗	35.1	BDL	47.2	BDL
4	Neck Right	11,017.2	3,249.4	9,545.3	5,977.4	3,437.7
5	Neck Left	7,463.5	4,192.6	7,080.3	3,901.8	4,645.2
6	Nape of Neck	2,080.9	451.5	1,169.3	BDL	298.8
19	Right Cheek	BDL	222.5	BDL	192.7	202.4
19A	Left Cheek	BDL	233.7	BDL	52.6	744.3

BDL = below detection limit *⊗ = missing PAD*
NA = not analyzed; PAD was positioned outside of the respirator

Table 14. Average MeS Penetration for All IPE Conditions

PAD ID	PAD Location	Suit (ng)	Helmet (ng)	Helmet+weight (ng)	Armor (ng)	Armor+collar (ng)
1	Scalp	403.5	10.0	102.7	74.5	50.6
1A	Forehead	81.1	132.3	105.8	75.6	359.0
2	Behind Left Ear Up	3,466.5	79.4	644.0	76.1	65.8
3	Behind Left Ear	7,038.2	1,201.3	1,103.4	1,297.9	1,289.9
4	Neck Right	13,622.9	8,758.1	11,003.6	8,675.2	7,342.4
5	Neck Left	13,767.5	10,967.8	8,105.8	6,426.0	8,198.7
6	Nape of Neck	4,947.4	2,041.9	1,899.2	1,424.9	1,676.9
19	Right Cheek	78.1	83.0	35.7	55.7	80.4
19A	Left Cheek	71.0	131.9	137.8	94.2	206.9

3.3.2 Calculation of MeS Protection Factors

The vapor protection factor (PF-V) at each PAD location *i* inside the ensemble was calculated using the equation

$$PF_i = \frac{OutsideDosage\left(\frac{mg * \min}{m^3}\right)}{InsideDosage\left(\frac{mg * \min}{m^3}\right)} \tag{3}$$

Inside dosage was calculated by multiplying the mass captured on each PAD by the uptake rate of the PAD sample lot. A MeS uptake rate of 0.022 L/min (2.2 x 10^{-5} m^3/min) was derived from lot acceptance tests performed by Dugway Proving Ground. Protection factors at each PAD location are presented in Tables 15 through 18 by test participant. Averages for PF-V against MeS vapor, derived from log transformed data, are shown in Table 19 for each IPE condition.

Table 15. Vapor PFs by IPE Condition for Test Participant 1

PAD ID	PAD Location	Suit	Helmet	Helmet+weight	Armor	Armor+collar
1	Scalp	386.9	7,434.0	6,556.3	709.8	⊗
1A	Forehead	7,158.0	7,434.0	6,556.3	333.5	6,987.9
2	Behind Left Ear Up	69.3	4,607.9	6,556.3	7,052.8	6,987.9
3	Behind Left Ear	12.1	7,434.0	274.7	22.4	40.1
4	Neck Right	3.3	5.2	3.7	4.7	6.4
5	Neck Left	3.1	5.6	9.7	3.9	5.2
6	Nape of Neck	10.1	84.5	512.4	20.5	450.1
19	Right Cheek	244.3	7,434.0	6,556.3	7,052.8	6,987.9
19A	Left Cheek	368.6	930.0	200.2	262.4	1,089.3

⊗ = *missing PAD*

Table 16. Vapor PFs by IPE Condition for Test Participant 2

PAD ID	PAD Location	Suit	Helmet	Helmet+weight	Armor	Armor+collar
1	Scalp	236.7	7,434.0	165.4	782.2	6,987.9
1A	Forehead	278.1	7,434.0	175.4	7,052.8	6,987.9
2	Behind Left Ear Up	15.2	7,434.0	34.6	251.2	95.6
3	Behind Left Ear	8.9	16.1	17.5	60.6	24.5
4	Neck Right	7.1	7.1	6.2	12.9	8.3
5	Neck Left	6.5	4.8	6.7	17.2	10.4
6	Nape of Neck	13.3	19.0	15.9	65.7	27.6
19	Right Cheek	7,158.0	7,434.0	713.1	7,052.8	6,987.9
19A	Left Cheek	897.0	7,434.0	1,168.4	1,341.7	6,987.9

Table 17. Vapor PFs by IPE Condition for Test Participant 3

PAD ID	PAD Location	Suit	Helmet	Helmet+weight	Armor	Armor+collar
1	Scalp	84.5	6,950.8	3,677.0	6,556.3	7,434.0
1A	Forehead	7,090.2	138.2	7,390.9	6,556.3	7,434.0
2	Behind Left Ear Up	14.1	631.3	1,082.1	6,556.3	452.3
3	Behind Left Ear	9.0	141.9	325.6	74.7	111.5
4	Neck Right	5.3	⊗	14.7	7.8	10.0
5	Neck Left	4.7	5.4	8.6	6,556.3	⊗
6	Nape of Neck	12.1	21.0	35.3	54.4	18.3
19	Right Cheek	7,090.2	770.6	2,620.9	6,556.3	695.0
19A	Left Cheek	7,090.2	328.5	⊗	6,556.3	7,384.8

⊗ = *missing PAD*

Table 18. Vapor PFs by IPE Condition for Test Participant 4

PAD ID	PAD Location	Suit	Helmet	Helmet+weight	Armor	Armor+collar
1	Scalp	209.5	6,950.8	6,624.9	789.6	515.9
1A	Forehead	1,223.7	6,950.8	6,624.9	NA	49.0
2	Behind Left Ear Up	⊗	375.6	135.7	7,090.2	758.1
3	Behind Left Ear	⊗	1,965.4	6,624.9	1,461.9	7,525.0
4	Neck Right	6.3	21.2	7.2	11.5	20.1
5	Neck Left	9.2	16.4	9.7	17.7	14.8
6	Nape of Neck	33.1	152.7	59.0	7,090.2	230.8
19	Right Cheek	7,390.9	309.9	6,624.9	357.7	340.7
19A	Left Cheek	7,390.9	295.1	6,624.9	1,310.6	92.6

⊗ = *missing PAD*

The lowest average PF-V values were found for the PADs positioned on the neck across all test conditions. Average in-mask PF-V for the forehead, right cheek, and left cheek PADs, all located within the respirator's peripheral seal, tended to be the highest for the majority of IPE conditions. Among these, in-mask PF-V were lowest for the left cheek PAD compared to the right cheek and forehead PADs across all conditions (Figure 18). However, no significant differences were observed among conditions for the individual forehead, right cheek, and left cheek PADs. Conservative estimates of respiratory protection against vapors based on the lowest average PF-V values of each of the in-mask PADs suggests the following levels of protection for each IPE condition: Suit = 2042, Helmet = 912, Helmet+weight = 1148, Armor = 1318, and Armor+collar = 1514.

Table 19. Average Log_{10} PF-V Based on PAD Location for All IPE Conditions

PAD ID	PAD Location	Suit	Helmet	Helmet+weight	Armor	Armor+collar
1	Scalp	2.30	3.86	3.36	3.11	3.48
		(200)	(7244)	(2290)	(1288)	(3020)
1A	Forehead	3.31	3.43	3.44	3.40	3.31
		(2042)	(2692)	(2754)	(2512)	(2042)
2	Behind Left Ear Up	1.39	3.23	2.63	3.48	2.84
		(25)	(1698)	(427)	(3020)	(692)
3	Behind Left Ear	1.00	2.63	2.50	2.04	2.23
		(10)	(427)	(316)	(110)	(170)
4	Neck Right	0.72	0.96	0.85	0.93	1.01
		(5)	(9)	(7)	(9)	(10)
5	Neck Left	0.74	0.84	0.93	1.72	0.97
		(6)	(7)	(9)	(52)	(9)
6	Nape of Neck	1.18	1.68	1.81	2.18	1.93
		(15)	(48)	(65)	(151)	(85)
19	Right Cheek	3.49	3.28	3.48	3.52	3.27
		(3090)	(1905)	(3020)	(3311)	(1862)
19A	Left Cheek	3.31	2.96	3.06	3.12	3.18
		(2042)	(912)	(1148)	(1318)	(1514)

() = average PF-V values

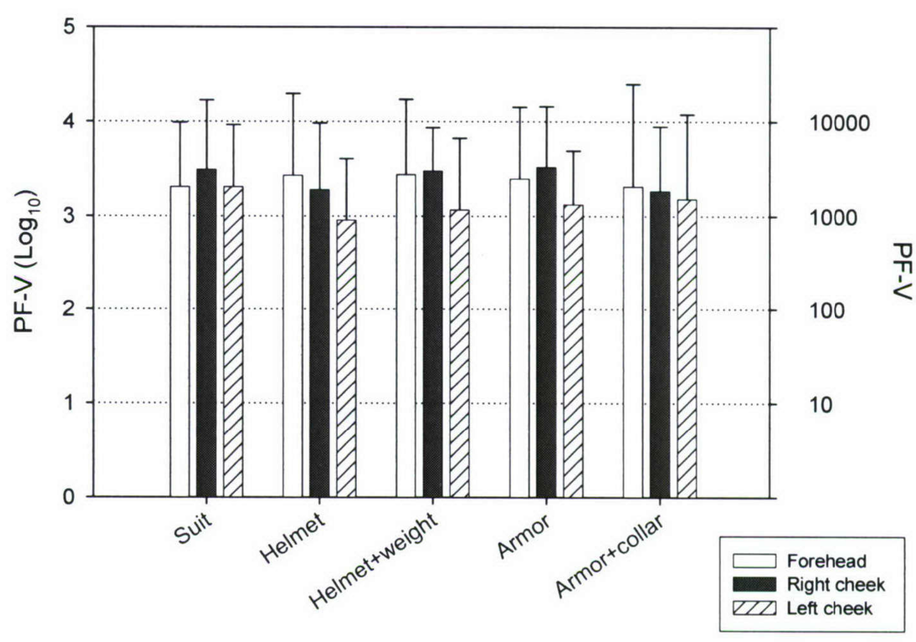


Figure 18. Average (±SD) PF-V for the In-mask PAD Samplers

4 DISCUSSION

4.1 AROM with IPE

In general, results for head AROM during simple head movements for the Control condition compared favorably with published norms for similarly aged individuals. Youdas et. al.[6] reported average AROM for leftward and rightward cervical rotation of 65 ± 9° and 67 ± 7°, respectively, for 30 – 39 year old males. Averages for the same AROM movement (i.e., Head S2S) were 61 ± 9° and 67 ± 8° in the present investigation. Data from Youdas et. al.[6] were also similar to findings presented herein for data obtained during the Head Lat Flex AROM activity for left (41 ± 10° vs. 37 ± 7°) and right (43 ± 9° vs. 38 ± 8°) lateral flexion. In contrast, averages for cervical flexion and extension for the Control condition during the Head Nod activity were less than values reported by others.[6] However, the ranges of cervical flexion and extension AROM values were similar. Therefore, these findings suggest that the methods and procedures utilized to quantify AROM of the head in this investigation were acceptable.

Reported AROM norms for hip flexion for individuals with demographics similar to the participants in this study average 123 ± 12° for women and 123 ± 9° for men.[7] During Lunge AROM exercises, left and right hip flexion averaged 109 ± 14° and 109 ± 15° for Control conditions. However, the range of values for the relatively small subject pool tested in this study was wide (73 – 132°) and comparable to ranges reported in the literature. Knee flexion AROM results for the Lunge and Step activities were also less than published values; however, differences in the AROM activities used to determine AROM among the various studies likely account for these differences. These comparisons further indicate that the techniques employed to measure AROM were also suitable for body regions other than the head.

To quantify the impacts of IPE wear on AROM, particularly the effects of head borne IPE, sequential levels of protective equipment items were added to the test matrix to simulate differing levels of respiratory and ballistic protection according to the conditions in Table 1. The one possible exception to this notion was the addition of the weight to the ballistic helmet to simulate head borne weight of a helmet-mounted night vision device. For the limited protection level of mask wear, no significant differences in joint AROM existed between the Control and Mask conditions for any of the AROM exercises performed in this study. Likewise, the largest performance decrement for the Mask condition was only roughly 9% (AROM PR = 91 ± 15%) for total AROM during head flexion and extension. In a similar comparison between bareheaded and masked conditions, Bensel et al.[8] also found a 10% reduction in head flexion and extension, albeit with a different style APR (U.S. Army M17) and the inclusion of a protective hood. Average AROM PR results for the Mask condition exceeded 95% for all other head AROM activities. Collectively, these findings suggest that, despite other known encumbrances associated with vision, breathing, and comfort, wearing an air-purifying respirator does not severely limit head AROM.

Impacts on AROM were evident beginning with the Suit condition, which included wear of the CB suit and Millennium respirator. For head movements, the most substantial impacts of the suit were observed during cervical rotation. The Suit AROM PR for this activity was only 75%, indicating a 25% decrement in performance. Because cervical rotation was not degraded for the mask only test condition, this decrement appears to be specific to the suit. Considering that Bensel et al.[8] found a comparable performance decrement in cervical rotation (i.e., 21%) for their mask and hood condition, it is probable that the hood of the CB suit itself is what caused the substantial reduction in cervical rotation.

Based on AROM PR results, notable performance decrements were also evident for total head flexion and extension (17%) and complete lateral flexion (15%). Decrements in head flexion and extension were likely caused by the combined impact of the mask and suit because a 9% decrement was found for the mask only condition, but the decrement in head lateral flexion appeared to be unique to the CB suit. Other AROM movements impacted by the CB suit included total thoracic rotation during the Twist exercise and hip flexion during the Bend & Reach and Lunge activities. These findings fall in line with other movement analysis research with protective overalls.[3,9]

The addition of the ballistic helmet to the protective equipment configuration caused significant reductions in most head AROM activities compared to the unencumbered Control and Mask conditions. For the most part, the weighted helmet condition had the same reductions in head AROM as those found for the Helmet condition. In general, head AROM in a single direction (i.e., left or right, up or down) for the Helmet condition did not change substantially compared to the Suit condition. However, total cervical rotation of the head for the H&K-Head S2S activity was significantly reduced during helmet wear compared to the Suit condition. Because additional muscle activity is needed to support the weight of the head in the crawling position relative to the standing position, it is possible that head rotation was limited due to additional muscle strain resulting from the weight of the helmet. Head rotation in this position may have also been limited by contact between the lateral protrusions of the helmet and the upper arms and shoulders. Some increase in head extension was also evident with the helmet compared to the Suit condition, but this was insignificant. As for other AROM activities, the addition of the ballistic helmet had no impact on any of the simple body movements and most of the complex body motions. Reasons for the significant decrease in hip flexion for the Helmet compared to the Control condition observed during the Sit AROM activity were not readily apparent. Additional data collection is needed to verify this finding and to ascertain its origins, particularly because it was not evident for the Helmet+weight condition. Although total thoracic rotation was reduced for the Helmet+weight condition compared to Control and Mask conditions, AROM PR results suggested only a 6% reduction in average performance. The reduction in thoracic flexion with the weighted helmet compared to Control and Mask conditions reflects feedback from test participants who commented that they didn't reach towards the floor as far as they could under this condition out of fear that the helmet was going to fall off. Thus, the most substantial impacts of ballistic helmet wear appear to be on movements involving cervical rotation. Again, additional research is warranted to validate decrements found for hip flexion during wear of the helmet with a suit and respirator.

Wear of the body armor vest not only impacted head AROM but also caused noticeable reductions in some whole body AROM. Although the vest did not appear to interfere with the mask or helmet, its relatively snug fit on the torso may have reduced the give or ease of the hood material of the CB suit, thus restricting head rotation AROM. The reductions in thoracic rotation (Twist activity) and thoracic flexion (Bend & Reach activity) during wear of the body armor vest were also likely due to reduced give of the suit material around the torso. However, the apparent reductions in suit ease with the vest did not cause noticeable differences between the Armor and Suit conditions for most AROM activities. The reduction in right shoulder flexion observed during the Pistol activity may have resulted from a reduction in suit ease and physical restrictions of the vest at the shoulder.

According to the AROM results, it was apparent that the Armor+collar test condition had the greatest impact on the movements performed in the present investigation compared to all of the other IPE test configurations. Based on the design and usage of the collar, these findings were not unexpected. The addition of the collar significantly decreased head flexion and extension and lateral flexion compared to all other IPE conditions and head rotation compared to all conditions other than the Armor concept. The interference between the front part of the neck collar and the mask, which were in contact with one another even in the neutral position, had the greatest impact on head flexion. Reductions in total thoracic rotation and shoulder abduction with the body armor collar were also significant compared to the other IPE conditions. Performance rating results, ranging from 47% to 80% for simple head movements and from 47% to 72% for simple body motions demonstrated just how severe the impacts of the collar were on these AROM movements. Other notable impacts of the collar were observed for thoracic flexion for the Bend & Reach activity, leftward cervical rotation during rifle simulation, and right shoulder flexion during pistol firing simulation. Together, these findings confirm that the optional high collar for added neck protection from ballistic threats severely limits AROM, particularly of the head.

4.2 Integrated CB and Ballistic IPE and Respiratory Protection from Aerosols

No significant decrements in PF-A existed with the progression of IPE items beginning with the Mask through to the Armor conditions. Meaningful changes in respiratory protection from an aerosol challenge were limited to two of the head rotation exercises and only for the Armor+collar condition. Based on the continuous contact between the respirator and collar observed for this condition, it is likely that momentary breakages in the seal between the face and the respirator occurred during the head rotation movements, thus impacting protection levels. Even so, overall PF-A results based on the harmonic average of PF data across all exercises did not differ among all IPE conditions and exceeded NIOSH requirements for CBRN APR. Therefore, respiratory protection from aerosols does not appear to be severely compromised by various integrated levels of CB and ballistic protection, particularly for items comparable to those assessed in this investigation.

Considering the AROM restrictions associated with the various IPE test conditions it is possible that PF-A results among conditions did not differ due to reduced AROM, which may have limited stresses associated with interactions of various IPE items that could influence respirator integrity. An example would be the interaction of the CB suit hood with the respirator periphery where pull of the hood on the mask would decrease as the ability to move the head was lessened by the restriction to movement imparted by the hood. As such, the chances of compromising the peripheral seal of the respirator to the face would be less and PF-A values would probably not be noticeably reduced. Because AROM data were not obtained during PF-A test trials, the degree to which this factor may or may not have influenced the PF-A findings presented herein is not known. However, because the only substantial drops in PF-A were associated with the most encumbering IPE use condition for the Armor+collar even though AROM reductions were found among all other IPE conditions, it appears that equipment bulk and incompatibility impacted respiratory protection more than anything.

4.3 Vapor Protection during Wear of Integrated CB and Ballistic IPE

The lowest average PF-V values found for the PADs positioned on the neck are in-line with previous findings on similar suits and likely reflect the open area of the CB suit where the front closure ended at the base of the neck.[10] The data among IPE conditions for the other PADs positioned under the hood of the suit, but outside of the respirator, varied considerably and no trends in the results were found. Vapor levels within the respirator face piece tended to be the lowest among the PADs for most IPE conditions, suggesting that the respirator seal and filter element prevented substantial inward leakage of the MeS simulant.

Average PF-V values of each of the in-mask PADs indicated PF-V levels between 912 and 2042 for all IPE conditions. However, the legitimacy of estimates of respiratory protection against vapors derived from the lowest average PF-V values of each of the in-mask PADs may be circumspect based on several limitations of the PADs. Included among these is variability in adsorption rates among PADs from the same sample lot when exposed to identical gas concentrations and the unquantified impacts of air flow rates and humidified air on PAD adsorption rates. In addition, it is questionable that the PAD placements defined by ASTM Standard F 2588-06 and U.S. Army TOP-2-022 for the head and face are adequate for defining vapor concentrations within the breathing zone of a respirator.[4,5] Other methods for measuring respirator gas/vapor protection factors employ continuous sampling of ambient and in-mask environments using two personal sampling pumps. However, the potential problems associated with continuous in-mask sampling of biased results due to lower contaminant concentrations caused by respirator dead volume and lung retention and high humidity in exhaled air have not been completely resolved by currently available measurement techniques.[11] As such, it is debatable that respirator PF-V data estimated from current methods and technologies have any real merit. Nevertheless, the data for MeS accumulation and calculated respirator PFs-V indicated that protection provided by the respirator was not impacted by the wear of additional IPE items progressing from the Mask through to the Armor conditions.

5. CONCLUSIONS

The results provided by this investigation quantified the effects of chemical and biological (CB) and ballistic individual protective equipment (IPE) items on head and body active range of motion (AROM) and respiratory protection from aerosol and vapor simulants. Wear of an air-purifying respirator (APR) alone did not significantly impact head AROM. However, substantial reductions in head AROM, mainly cervical rotation, were evident with the addition of the CB suit, ballistic protective helmet, and body armor. Reductions in AROM for regions other than the head were found primarily for body armor test conditions. Despite these notable decrements in head and body mobility with increasing levels of protective equipment wear, respiratory protection levels were relatively consistent among IPE conditions. For the potential users of the CB and ballistic IPE items such as those assessed in this investigation these findings indicate that increasing amounts of IPE wear will decrease AROM for many common head and body movements. Knowing the decrements in AROM associated with CB and ballistic IPE items should help users develop strategies to compensate for lost mobility without severely impacting their abilities to perform their work. The fact that overall respiratory protection levels were not influenced by the differing levels of IPE wear should help alleviate concerns that interactions of CB and ballistic IPE for law enforcement personnel can substantially decrease protection from environmental contaminants.

One additional application of the results of this study is the potential for defining IPE performance criteria based on AROM and protection. Establishing such criteria would help to ensure that individual IPE items would not only fit properly but also function together so that wearer movement is not inhibited. The limited numbers of IPE conditions assessed in this investigation prevent the development of robust IPE performance criteria. Nevertheless, some criteria have been drafted for publication under separate cover. To enhance IPE performance criteria based on AROM, the methodology utilized in this study should be used to evaluate other models and types of CB protective respirators and clothing, as well as different ballistic protective equipment, and their impacts on AROM and respiratory protection from aerosol challenges. However, alternative methods for quantifying respiratory protection from gases and vapors need to be investigated before definitive answers concerning vapor protection afforded by respirators can be determined. Evaluations of clothing protection from aerosols and vapors during AROM should also be considered in future work.

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APPENDIX
PHOTOGRAPHS OF SELECT IPE TEST CONDITIONS

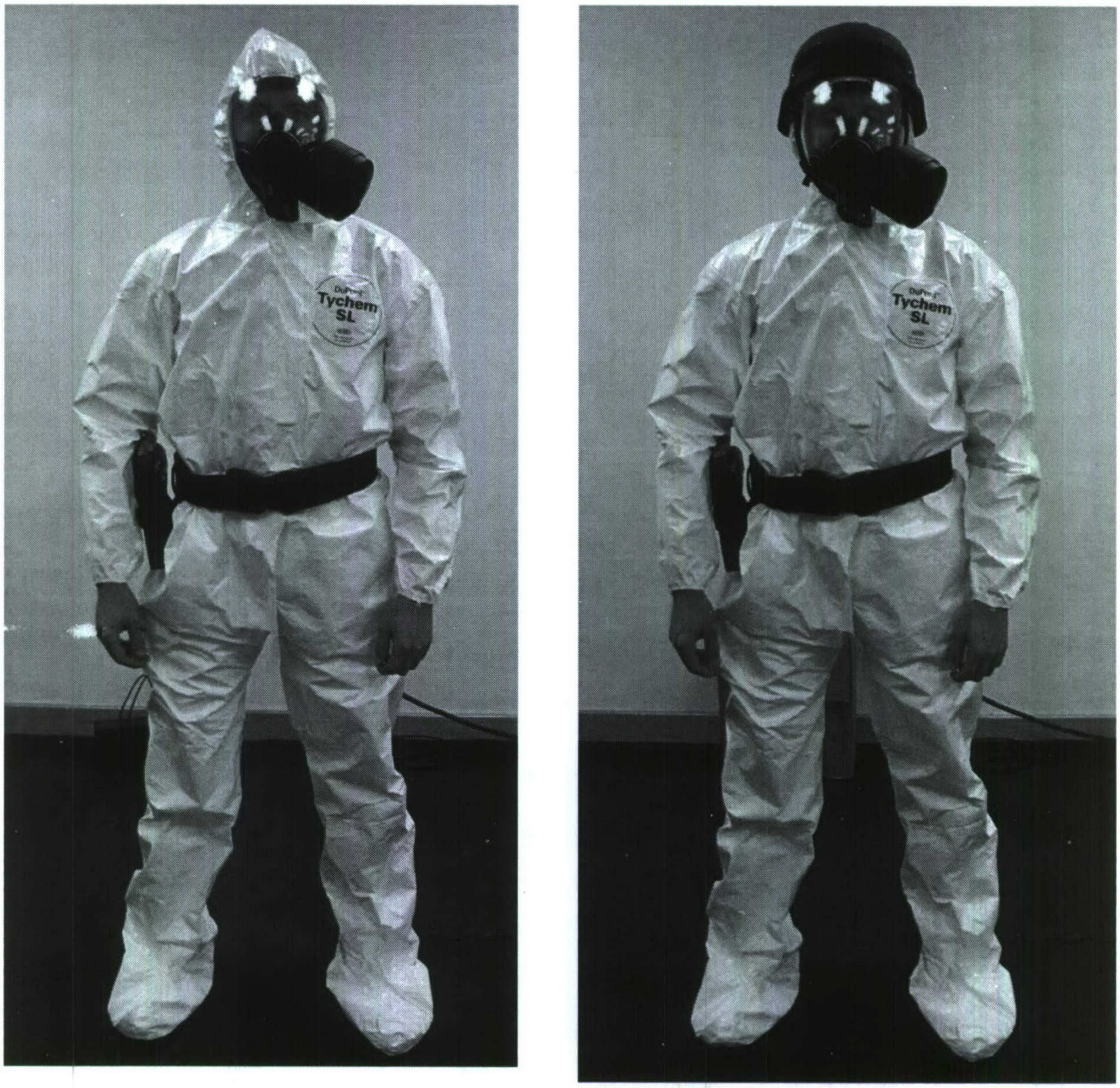

Figure 1. Suit (left) and Helmet Test Conditions

Figure 2. Helmet+Weight (left) and Armor Test Conditions

Figure 3. Front and Side View of the Armor+Collar Test Condition