

Impacts of Respirator, Suit, and Helmet Wear on Head and Upper Body Range of Motion

David M. Caretti

U.S. Army Edgewood Chemical Biological Center, Aberdeen Proving Ground, MD 21010

E-mail: david.caretti@us.army.mil

ABSTRACT

This investigation quantified active range of motion (AROM) of subjects wearing chemical/biological (CB) and ballistic individual protective equipment (IPE). To quantify the impacts of IPE wear on AROM, sequential levels of protective equipment items were added to a test matrix to simulate differing levels of respiratory and ballistic protection compared to a control condition. AROM data were collected from 10 subjects during 5 head and 3 upper body AROM activities and analyzed for specific joint axes depending upon the AROM exercise. Results indicated that wearing a full facepiece air-purifying respirator alone did not significantly impact head AROM. However, substantial reductions in head AROM performance ratings, mainly cervical rotation (range 9%-37%), were evident with the addition of the CB suit, ballistic protective helmet, and a body armor vest. Reductions in AROM for regions other than the head were found primarily for body armor test conditions. These findings quantify reductions in AROM based upon representative CB and ballistic IPE items and indicate that increasing amounts of IPE wear will decrease AROM for many common head and body movements.

Keywords: Active range of motion, respirator, individual protective equipment, head, upper body

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 (Gowitzke and Milner, 1981). Range of motion is also impacted by restraints imposed by individual protective chemical and biological (CB) equipment items and ballistic protective equipment (Watkins, 1995). For instances where a police officer or soldier would need to wear ballistic protective helmets and vests along with some level of chemical protective clothing and a protective respirator, hindrances on movement could conceivably be detrimental and possibly life threatening. Even so, there is little empirical data that quantifies movement restrictions due to wear of individual protective equipment (IPE). This dearth 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 (Huck and Kim, 1997). Therefore, the purposes of this investigation were to determine normal values for active range of motion (AROM) of individuals performing common head and body movements and to quantify the impacts of wearing individual CB and ballistic protective equipment

on AROM. Since respirator design and development are of principal significance to the test organization, interactions of a respirator with head borne IPE items and those which are positioned adjacent to the head and neck were of particular interest.

MATERIALS AND METHODS

Subjects

Ten subjects (eight males and two females) between the ages of 18 and 45 (35 ± 9 yr) participated in this study. All volunteers were civilians employed at the Edgewood Chemical Biological Center 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 Safety and Health 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, Aberdeen Proving Ground, MD.

Experimental Conditions

The specific IPE configurations that were tested are listed in Table I and presented in Figure 1. The Millennium[®] Chemical, Biological, Radiological, and Nuclear (CBRN) Gas Mask (Mine Safety Appliances, Pittsburgh, PA) was worn for all conditions requiring respirator wear. The Millennium is a full-facepiece, air-purifying respirator (APR) certified by the National Institute for Occupational Safety and Health (NIOSH) as meeting all performance requirements of the NIOSH CBRN APR Standard. For this test, the filter element of the APR was mounted on the left side of the facepiece for all participants. The active wear clothing condition included 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 (DuPont), with an integral hood, elastic wrist 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; Mine Safety Appliances, Pittsburgh, PA) was the ballistic helmet used for helmet wear conditions. The BlackHawk[®] S.T.R.I.K.E. Cutaway Tactical Armor Vest (BlackHawk Products Group, Norfolk, VA) was utilized for conditions calling for ballistic vest wear. The vest is lightweight (1.6 Kg) with an adjustable waist and shoulder system for tailoring girth and torso length for improved fit. 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 I. 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
Armor	Respirator, CB suit, ballistic helmet, and ballistic vest



Mask



Armor



Suit



Helmet

Figure 1. Experimental individual protective equipment (IPE) conditions.

Range of Motion Test Procedures

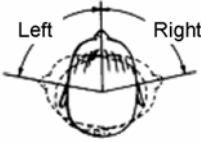
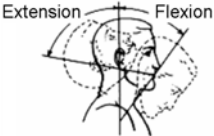
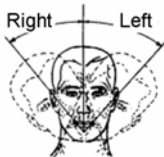
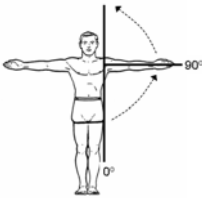
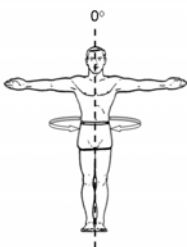
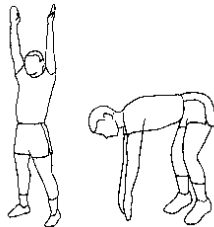
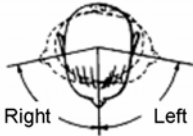
Upon arrival to the lab, subjects changed into active wear clothing and were prepped for testing. First, a Millennium respirator, Tychem® SL suit, and ACH-C helmet were properly sized and assigned to a subject by test facility personnel. Subjects then donned nine body-mounted range-of-motion sensors 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 so the user is 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 2.5-cm cube attached via a wire to an electronics unit that was mounted in a cloth pouch attached to a small (18 cm x 14 cm x 5 cm) backpack that weighed 1.5 Kg with the electronics unit. 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: middle of the biceps of the left and right arms, left and right wrists, left and right legs just below the knees, back of the head (external occipital protuberance), neck (vertebra prominens), and lower back (median crest of the sacrum). 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 a neutral position (i.e., arms hanging at the side, head looking forward) in the center of the measurement field.

Testing commenced once operation of the AROM equipment was confirmed. Experimental test conditions were administered in sequence starting with Control conditions, followed by Mask, Suit, Helmet, and Armor conditions. Although a training effect was considered using this sequence of testing, rest periods and donning times experienced between conditions (range between 5 and 20 min), as well as the short duration of AROM activities, were expected to minimize any significant training effect on AROM. Test personnel assisted subjects with IPE donning to prevent displacement of any of the range of motion sensors. Active range of motion for various body joints was measured and recorded as test participants performed the movements listed in Table II. 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 judged 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 so that subjects would perform them uniformly with the exception of the following: traffic control movements, shouldering the rifle, and sighting the pistol. 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 min between test conditions.

Table II. Activities Used to Assess AROM and the AROM Variables Analyzed for Each Movement

Range of Motion Activity	Graphic Depiction	Description	AROM Variables
Rotate head side-to-side (Head S2S)		Standing in place, subjects slowly turned the head from side-to-side	Left and right cervical rotation; total cervical rotation
Flex head up and down (Head Nod)		Standing in place, subjects slowly moved the head up and down	Cervical flexion and extension; full range of flexion and extension
Flex head to the left and right (Head Lat Flex)		Standing in place, subjects slowly flexed the head to the left as if to touch the left ear to the left shoulder and then repeated the motion to the right	Left and right cervical lateral flexion; total lateral flexion
Upper arm movements (Arms up)		Standing in place, subjects raised both arms sideward and upward with the palms facing forward until the hands moved as far as possible over the head without bending the elbows	Shoulder abduction
Twisting at waist (Twist)		While standing, subjects extended arms to the sides of torso and twisted at the waist from side-to-side	Left and right thoracic rotation; total thoracic rotation
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	Left and right cervical rotation
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	Shoulder flexion and extension; thoracic flexion
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	Left and right cervical rotation; total cervical rotation

Analysis of AROM Data

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

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

where AROM_{IPE} = joint range of motion for an individual AROM activity and IPE test condition and AROM_{C} = joint range of motion under Control conditions for the same activity. The denominator represents the average of all AROM_{C} for an individual subject. 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). The maximum number of data points for any AROM variable was 30 (3 trials per subject X 10 subjects). 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.

RESULTS

AROM of the Cervical Spine for Head Motions

Results for cervical AROM data are presented in Table III. The data are expressed as mean $\pm$ 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, subject availability for testing, and completion of additional AROM measurement periods for some subjects resulted in differences in the number of data points analyzed for each IPE test condition. For some instances, sensor displacement was observed during IPE donning, particularly when adding the suit. When displacement went unnoticed with IPE donning, significant sensor displacement was obvious after the first occurrence of data acquisition when graphical results of the AROM activity were displayed on the computer screen. When plausible, displaced sensors were repositioned and an additional sensor digitization routine was performed.

Compared to Control, cervical rotation to the right was significantly reduced for all conditions but the Mask during the Head S2S AROM exercise. In addition, the Helmet and Armor conditions differed significantly from the Mask condition. Cervical rotation to the left was also significantly less for the Armor condition compared to the Control and the Mask, but no other differences among conditions were found for this AROM activity.

For the Head Nod activity, head extension did not differ among conditions. However, head flexion was reduced significantly for the Helmet and Armor conditions compared to Control. During lateral head flexion, left lateral flexion of the head did not differ among all IPE test conditions. Right

lateral head flexion was lower for all test conditions compared to Control, but the only significant difference occurred between the Helmet and Control concepts.

Table III. Mean ($\pm$ SD) Cervical AROM Data (degrees) for Head AROM Movements

AROM Activity	AROM Variable	IPE Condition				
		Control (N = 27)	Mask (N = 21)	Suit (N = 24)	Helmet (N = 25)	Armor (N = 18)
Head S2S	Rotation – Right	67.0 $\pm$ 7.9	64.0 $\pm$ 10.2	56.2 $\pm$ 11.2 ^a	50.4 $\pm$ 9.3 ^{a,b}	49.4 $\pm$ 16.0 ^{a,b}
	Rotation – Left	62.0 $\pm$ 8.9	59.5 $\pm$ 11.3	53.0 $\pm$ 12.7	52.1 $\pm$ 14.0	45.9 $\pm$ 11.3 ^{a,b}
	Rotation – Total	129.0 $\pm$ 14.2	123.5 $\pm$ 9.6	109.2 $\pm$ 22.0 ^a	102.5 $\pm$ 18.4 ^{a,b}	95.4 $\pm$ 21.6 ^{a,b}
Head Nod	Flexion	48.9 $\pm$ 11.9	38.3 $\pm$ 15.2	42.2 $\pm$ 10.9	34.3 $\pm$ 11.6 ^a	32.5 $\pm$ 12.2 ^a
	Extension	41.9 $\pm$ 15.0	41.7 $\pm$ 17.8	33.3 $\pm$ 20.3	47.0 $\pm$ 18.0	36.4 $\pm$ 15.7
	Total	90.9 $\pm$ 14.1	80.0 $\pm$ 16.0	75.5 $\pm$ 16.4 ^a	81.3 $\pm$ 18.1	68.9 $\pm$ 9.1 ^a
Head Lat Flex	Lat Flex – Right	37.5 $\pm$ 8.3	34.5 $\pm$ 9.4	30.3 $\pm$ 7.7	29.0 $\pm$ 10.4 ^a	29.8 $\pm$ 7.9
	Lat Flex – Left	36.6 $\pm$ 7.6	34.5 $\pm$ 11.3	31.9 $\pm$ 8.2	36.3 $\pm$ 11.0	33.6 $\pm$ 10.5
	Lat Flex – Total	74.1 $\pm$ 10.7	69.1 $\pm$ 13.7	62.3 $\pm$ 14.3 ^a	65.3 $\pm$ 11.4	63.4 $\pm$ 11.7
H&K Head S2S	Rotation – Right	73.3 $\pm$ 9.9	65.2 $\pm$ 14.0	53.9 $\pm$ 13.2 ^{a,b}	44.0 $\pm$ 8.9 ^{a,b}	42.5 $\pm$ 12.7 ^{a,b}
	Rotation – Left	67.2 $\pm$ 12.0	62.4 $\pm$ 11.8	48.4 $\pm$ 14.2 ^{a,b}	39.9 $\pm$ 11.5 ^{a,b}	38.5 $\pm$ 12.3 ^{a,b}
	Rotation – Total	140.4 $\pm$ 19.6	127.5 $\pm$ 15.8	102.3 $\pm$ 24.6 ^a	83.9 $\pm$ 16.2 ^{a,b,c}	81.0 $\pm$ 17.8 ^{a,b,c}
Traffic	Rotation – Right	41.4 $\pm$ 19.8	38.7 $\pm$ 25.2	33.9 $\pm$ 14.5	30.0 $\pm$ 11.9	29.4 $\pm$ 13.2
	Rotation – Left	42.2 $\pm$ 10.3	42.6 $\pm$ 15.8	31.8 $\pm$ 8.8	32.0 $\pm$ 10.2	26.6 $\pm$ 12.9 ^{a,b}
	Rotation – Total	84.8 $\pm$ 16.1	82.3 $\pm$ 17.8	65.7 $\pm$ 19.0 ^a	62.0 $\pm$ 16.6 ^{a,b}	56.0 $\pm$ 22.4 ^{a,b}

^a = significantly different from Control

^b = significantly different from Mask

^c = significantly different from Suit

In addition to the Head S2S movements, cervical rotation was also assessed during the H&K-Head S2S and Traffic AROM activities. For the H&K-Head S2S exercise, cervical rotation was not impacted by the Mask only condition. However, the Suit, Helmet, and Armor IPE conditions all caused significant reductions in both leftward and rightward cervical rotation compared to Control and Mask conditions. In contrast, cervical rotation to the right during the Traffic exercise did not differ significantly among test conditions, but leftward rotation was significantly reduced for the Armor condition compared to both Control and Mask results.

Total head AROM data representing the full range of movement about the cervical axis are also presented in Table III. Total cervical rotation with the Suit condition was significantly less compared to

Control for the Head S2S, H&K Head S2S, and Traffic exercises. Likewise, significant reductions in total cervical rotation for the Helmet and Armor conditions compared to both the Control and Mask concepts were evident for the same activities. Total cervical rotation for both the Helmet and Armor conditions also differed significantly from the Suit results during the H&K Head S2S motion. Total AROM for head flexion and extension was similar among most IPE conditions with the exception of the Suit and Armor, which were significantly less compared to the Control condition. Even though total head lateral flexion was reduced for all experimental IPE conditions compared to Control, the only significant difference observed among conditions was between Suit and Control results.

Performance decrements in total cervical rotation for all head rotation activities varied considerably among AROM exercises (Table IV). Performance ratings in excess of 100% indicate that some subjects exceeded maximal AROM ranges under certain IPE conditions and the sizeable standard deviations demonstrate the variance in the data. No significant performance reductions were evident for the Head S2S and Traffic activities. Mean AROM PR data for total head rotation for the H&K Head S2S activity indicated a significant performance decrement in cervical rotation for the Suit, Helmet, and Armor conditions compared to the Mask condition. Cervical rotation performance ratings with the Helmet and Armor also differed significantly compared to the Suit condition and averaged nearly a 40% reduction in performance. AROM performance rating results for total range of movement for cervical flexion and extension showed decrements in performance ranging between 10% and 20% for all IPE conditions. The Armor condition caused the greatest performance decrement in total cervical flexion and extension with a PR that differed significantly from the Mask condition. No significant performance decrements were found among IPE conditions for total lateral head flexion.

Table IV. Mean Percent Performance Ratings ($\pm$ SD; (N)) for Total Cervical AROM

AROM Activity	AROM Variable	IPE Condition			
		Mask	Suit	Helmet	Armor
Head S2S	Rotation	106 $\pm$ 21 (21)	91 $\pm$ 24 (24)	87 $\pm$ 32 (25)	86 $\pm$ 35 (18)
Head Nod	Flexion & Extension	91 $\pm$ 15 (21)	83 $\pm$ 12 (24)	89 $\pm$ 15 (25)	79 $\pm$ 9 ^b (18)
Head Lat Flex	Lat Flex	96 $\pm$ 12 (21)	85 $\pm$ 17 (24)	89 $\pm$ 18 (25)	91 $\pm$ 19 (18)
H&K Head S2S	Rotation	95 $\pm$ 6 (21)	75 $\pm$ 16 ^b (24)	61 $\pm$ 11 ^{b,c} (25)	63 $\pm$ 16 ^{b,c} (18)
Traffic	Rotation	98 $\pm$ 11 (19)	82 $\pm$ 25 (22)	80 $\pm$ 31 (24)	78 $\pm$ 41 (17)

^b = significantly different from Mask

^c = significantly different from Suit

AROM for Arm and Torso Motions

Results for AROM data for the arm and torso movements assessed in this study are presented in Table V. The Armor condition produced the lowest shoulder abduction AROM results for the Arms Up activity. However, no significant differences among IPE conditions were evident for either left or right shoulder abduction.

Thoracic rotation during the Twist activity differed little among the IPE test conditions in either direction with the following exception: rotation to the right was significantly less for the Armor condition

compared to both the Control and Mask conditions. Total thoracic rotation (i.e., complete rotation to the left and right) was reduced for all IPE conditions involving wear of the CB protective suit. Compared to Control, significant differences were observed for the Suit and Armor conditions. The difference between Control and Helmet conditions did not reach significance ($p = 0.11$). Total thoracic rotation also differed significantly between the Armor and Mask conditions.

The motions analyzed for the Bend & Reach AROM exercise were thoracic flexion and left and right shoulder flexion. Thoracic flexion was reduced for all conditions of chemical suit wear compared to the non-suit conditions (i.e., Control and Mask). However, the only significant reductions in thoracic flexion were observed between the Control and Armor concepts and the Mask and Armor conditions. Left and right shoulder flexion did not differ among all IPE test conditions.

Table V. Mean ($\pm$ SD; (N)) Arm and Torso AROM Results (degrees)

ROM Activity	AROM Variable	IPE Condition				
		Control	Mask	Suit	Helmet	Armor
Arms Up	Left Shoulder	145.6 $\pm$ 14.0	141.3 $\pm$ 15.9	132.2 $\pm$ 14.0	132.7 $\pm$ 15.0	130.8 $\pm$ 15.6
	Abduction	(27)	(25)	(21)	(25)	(15)
	Right Shoulder	133.6 $\pm$ 16.7	136.0 $\pm$ 20.1	128.8 $\pm$ 17.0	138.5 $\pm$ 20.7	119.4 $\pm$ 11.8
	Abduction	(27)	(25)	(21)	(25)	(15)
Twist	Thoracic Rotation – Right	37.0 $\pm$ 9.2 (27)	38.7 $\pm$ 14.6 (21)	33.2 $\pm$ 5.8 (25)	34.3 $\pm$ 8.5 (22)	26.8 $\pm$ 12.2 ^{a,b} (18)
	Thoracic Rotation – Left	38.8 $\pm$ 8.8 (27)	35.6 $\pm$ 9.1 (20)	31.2 $\pm$ 10.6 (27)	33.7 $\pm$ 14.4 (18)	31.5 $\pm$ 7.3 (18)
	Thoracic Rotation – Total	75.7 $\pm$ 12.3 (27)	73.4 $\pm$ 12.3 (20)	64.2 $\pm$ 11.4 ^a (25)	65.7 $\pm$ 15.7 (18)	58.3 $\pm$ 8.8 ^{a,b} (18)
Bend & Reach	Left Shoulder Flexion	146.0 $\pm$ 16.5 (27)	145.6 $\pm$ 16.4 (21)	146.5 $\pm$ 9.9 (24)	150.9 $\pm$ 11.2 (25)	137.8 $\pm$ 13.2 (18)
	Right Shoulder Flexion	146.9 $\pm$ 19.2 (27)	146.2 $\pm$ 19.2 (21)	146.4 $\pm$ 16.6 (24)	143.9 $\pm$ 12.9 (24)	137.4 $\pm$ 12.3 (18)
	Thoracic Flexion	60.3 $\pm$ 20.8 (24)	60.7 $\pm$ 23.3 (21)	47.2 $\pm$ 15.5 (24)	45.4 $\pm$ 16.3 (22)	40.1 $\pm$ 11.9 ^{a,b} (18)

^a = significantly different from Control

^b = significantly different from Mask

^c = significantly different from Suit

Performance ratings for AROM results obtained during the Arms Up exercise ranged from 87% to 98% for left shoulder abduction and from 95% to 106% for right shoulder abduction. No significant differences in right shoulder abduction PR results were evident among IPE conditions. In contrast, left shoulder PR results for the Mask condition (98 $\pm$ 8%) were significantly better compared to the Suit (88 $\pm$ 6%), Helmet (92 $\pm$ 8%), and Armor (87 $\pm$ 13%) conditions.

AROM PR results for total thoracic rotation during the Twist activity differed significantly for the Mask (99 $\pm$ 9%) compared to the Suit (84 $\pm$ 11%), Helmet (86 $\pm$ 16%), and Armor (82 $\pm$ 15%) conditions. However, no significant differences in total thoracic rotation PR results were evident among the Suit, Helmet, and Armor conditions.

For the Bend & Reach activity, thoracic flexion performance ratings averaged $97 \pm 23\%$, $87 \pm 27\%$, $71 \pm 19\%$, and $71 \pm 14\%$ for the Mask, Suit, Helmet, and Armor conditions, respectively and the Mask PR results differed significantly from all IPE concepts. Performance ratings ranged between roughly 96% and 103% for both left and right shoulder flexion during the Bend & Reach activity, but no significant differences among test conditions were observed for AROM PR values calculated for left and right shoulder flexion.

DISCUSSION

In general, results for head AROM during head movements for the Control condition of this investigation compared favorably with published norms for similarly aged individuals. Youdas et. al. (1992) reported average AROM for leftward and rightward cervical rotation of $65 \pm 9^\circ$ and $67 \pm 7^\circ$, respectively, for 30 – 39 year old males. Averages for the same AROM movement (i.e., Head S2S) were $61 \pm 9^\circ$ and $67 \pm 8^\circ$ in the present investigation. Data from Youdas et. al. (1992) were also similar to findings presented herein for data obtained during the Head Lat Flex AROM activity for left ($41 \pm 10^\circ$ vs. $37 \pm 7^\circ$) and right ($43 \pm 9^\circ$ vs. $38 \pm 8^\circ$) 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 (NASA, 2008; Youdas et. al., 1992). However, the ranges of cervical flexion and extension AROM values were similar. These findings suggest that the methods and procedures utilized to quantify AROM of the head in this investigation were suitable.

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 I. No significant differences in joint AROM were observed between the Control and Mask conditions for any of the AROM exercises performed in this study. Additionally, the largest performance decrement for the Mask condition was only about 9% (AROM PR = $91 \pm 15\%$) for total cervical AROM during head flexion and extension. Average AROM PR results for the Mask condition exceeded 95% for all other head AROM activities. In a similar comparison between bareheaded and masked conditions, Benseal et. al. (1987) also reported a 10% reduction in head flexion and extension, albeit with a different style full facepiece APR (U.S. Army M17). Collectively, these results indicate that, despite other known encumbrances associated with vision, breathing, and subjective comfort, wearing a full-facepiece APR does not severely limit head AROM (Carette and Coyne, 2006; Johnson et. al., 2005; Carette, 1996).

Impacts on AROM with IPE were most 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 test condition, this decrement appears to be specific to the suit. Considering that Benseal et. al. (1987) reported 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%) with the Suit condition. 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 (Huck and Kim, 1997; Huck et. al., 1996).

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. 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 (Thuresson et. al. 2003). 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 measureable impact on any of the arm and torso movements. Thus, the most substantial impacts of ballistic helmet wear appear to be on movements involving cervical rotation.

Wear of the body armor vest not only impacted head AROM but also caused noticeable reductions in some whole body AROM. Although there was no noticeable interference between the vest and the respirator 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. However, any limitations in give of the suit's hood due to the vest were only found during the H&K Head S2S movements, a posture that likely reduced suit ease the most. 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, since any reductions in suit ease with the vest did not cause noticeable differences between the Armor and Suit conditions for all AROM activities other than the H&K Head S2S exercise, the overall impact of the body armor vest on AROM was minimal compared to the impacts of the CB suit in and of itself.

The effects that reductions in AROM associated with the IPE items assessed in this investigation may have on operational task performance cannot be determined from the results. Intuitively, minimizing range of motion decrements should be advantageous when it comes to performing job tasks. However, Coca et. al. (2008) found that even minor differences in range of motion between firefighter ensembles had no impacts on performance of job-specific tasks. Therefore, additional research seems necessary to define performance losses of AROM that actually lead to loss of operational task performance.

CONCLUSIONS

The results provided by this investigation quantified the effects of CB and ballistic IPE items on head and upper body AROM. Wear of a CBRN certified full facepiece 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. In general, the largest reductions in head AROM were associated with the hooded CB suit. Reductions in AROM for regions other than the head were found primarily for body armor test 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. In addition, the results of this study could help define 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.

REFERENCES

- Caretti DM and Coyne KM. (2006) A Quantitative Review of Ventilation Rates during Respirator Resistance Breathing. *J. ISRP* 23:1-20.
- Caretti DM. (1996) Effect of Full Face-Piece Respirator Design on Detection of Peripherally Located Stimuli. *J. ISRP* 14:11-18.
- Coca A, Roberge R, Shepherd A, Powell JB, Stull JO, and Williams WJ. (2008) Ergonomic Comparison of a Chem/Bio Prototype Firefighter Ensemble and a Standard Ensemble. *Eur. J. Appl. Physiol.* 104:351-359.
- Bensel CK, Teixeira RA, and Kaplan DB. (1987) *The Effects of U.S. Army Chemical Protective Clothing on Speech Intelligibility, Visual Field, Body Mobility and Psychomotor Coordination of Men*. U.S. Army Natick Research, Development and Engineering Center. NATICK-TR-87/037. UNCLASSIFIED Report.
- Gowitzke BA and Milner M. (1981) *On the Skeletal System. In Understanding the Scientific Basis for Human Movement*; 2nd ed. Baltimore: Williams and Wilkins Company, 1-39.
- Huck J and Kim Y. (1997) Coveralls for Grass Fire Fighting. *Int. J. Clothing Sci. Technol.* 9:346-359.
- Huck J, Maganga O, and Kim Y. (1996) Protective Overalls: Evaluation of Garment Design and Fit. *Int. J. Clothing Sci. Technol.* 9:45-61.
- Johnson AT, Scott WH, Phelps SJ, Caretti DM, and Koh FC. (2005) How is Respirator Comfort Affected by Respiratory Resistance? *J. ISRP* 22:38-46.
- National Aeronautics and Space Administration (NASA) (2008) Man-Systems Integration Standards, Volume I-Standards, Section 3: Anthropometry and Biomechanics; NASA-STD-3000. <http://msis.jsc.nasa.gov/sections/section03.htm>.
- Roach KE and Miles TP. (1991) Normal Hip and Knee Active Range of Motion: The Relationship to Age. *Phys. Ther.* 71:656-665.
- Thuresson M, Ang B, Linder J, and Harms-Ringdahl K. (2003) Neck Muscle Activity in Helicopter Pilots: Effects of Position and Helmet-mounted Equipment. *Aviat. Space Environ. Med.* 74:527-532.
- Watkins SM. (1995) *The Design Process. In Clothing: The Portable Environment*; 2nd ed. Ames: Iowa State University Press, 334-355.
- Youdas JW, Garrett TR, Suman VJ, Bogard CL, Hallman HO, and Carey JR. (1992) Normal Range of Motion of the Cervical Spine: An Initial Goniometric Study. *Phys. Ther.* 72:770-780.