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Postural Sway Measurements: A Potential Safety Monitoring Technique for Workers Wearing Personal Protective Equipment

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This study investigated the use of postural sway measurements as a potential safety monitoring technique. Sixteen healthy male volunteers (age: 41.8 ± 9.3 years) participated in this study. The level of neurophysiological strain and the ability to maintain upright balance for workers wearing personal protective equipment (PPE) were investigated. Three levels of PPE, the United States Environmental Protection Agency (USEPA)-defined levels A, B, and C, were worn in random order while performing two randomly ordered tasks, resting and a workload. After the workload task, the perceived exertion and discomfort were recorded. Postural sway, measured using a microprocessor-based force platform system, was assessed after each task. The variables of sway area and sway length were calculated from stabilograms. These measurements were taken for three sway tests: 1) Eyes open (EO), 2) Eyes closed on a four-inch foam (FC), and 3) a dynamic test with the subject reaching for a weight placed in front, lifting it to his or her chest, and lowering back to the shelf four times (RE). The heart rate was significantly higher for the workload task ($p < 0.05$), and the levels A and B PPE demonstrated significantly higher perceived exertion results than level C PPE ($p < 0.05$). The heart rate and perceived exertion were not significantly correlated with the sway measurements. Level A produced significant self-reported discomfort results for the upper back, lower back, and thighs. The sway variables showed significant differences with the PPE levels and the task. The workload task produced significantly higher sway length than the resting task ($p < 0.05$) for all test conditions. The PPE level B produced significantly higher sway length than PPE level A ($p < 0.05$) in the FC test condition. These results indicate that postural stability is altered with PPE use and with fatigued postural muscles. In summary, postural sway measurements may be used as a potential safety monitoring technique.

Keywords Personal Protective Equipment, Postural Sway Measurements, Safety Monitoring Technique

Workers entering a hazardous waste site must be protected from the site's potential chemical, physical, or biological hazards. Personal protective equipment (PPE) is one of the methods used to provide a barrier that isolates workers from these potential hazards. The use of PPE, however, can be hazardous in itself because of the physiological and biomechanical strain on the worker caused by the equipment. Heat stress and additional workload due to wearing PPE can cause physiological strain that may alter the neuromuscular performance of a hazardous waste worker.(1)

Various levels of protection are defined by the United States Environmental Protection Agency (USEPA) that range from minimal dermal and respiratory protection, level D, to maximal protection, level A. The higher levels of PPE tend to have higher associated risks.(2) Risks can include both physical and psychological stress as a result of heat stress, impaired vision and communication, weight of PPE, and decreased mobility. The amount and type of PPE have a relationship with the risk of physiological strain, primarily heat strain, on a worker.(1,3–9) Heat or thermoregulatory stress is a common health hazard while wearing PPE, since the protective material limits the dissipation of body heat and moisture essential for cooling.(10) In addition to thermoregulatory stress, cardiorespiratory stress can also affect the worker.(4) The neurophysiological strain can be caused by a number of factors including environmental factors, clothing ensemble, physical workload, and the specific characteristics of each worker.(2) This provides a potential safety hazard because of the PPE's effect on the upright postural balance and motor skills of the worker in a potentially dangerous environment.

Monitoring techniques for the safety of workers wearing PPE in the field are limited. The National Institute for Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration (OSHA), the United States Coast Guard

(USCG), and the USEPA recommend monitoring for heat stress and other physiological factors for workers wearing protective clothing in their Standard Operating Safety Guides.[2] The American Conference of Governmental Industrial Hygienists' (ACGIH®) threshold limit values (TLVs®) for heat stress[11] also provide guidelines and correction factors for workers wearing PPE. Other methods include monitoring heart rate, oral temperature, and body water loss.

To maintain upright balance, a person must keep their center of gravity (CG) inside the base of support (BOS) created by their foot placement. The position of a person's CG is constantly changing as sensory information (visual, somatosensory, and vestibular) alters motor function to accommodate the effect of gravity.[12] The result of the continual compensation by the postural muscles to keep the CG within the BOS produces postural sway. In the case of biomechanical stress altering the position of a worker's CG or BOS due to weight or equipment dimensions, additional compensation must be made. The central nervous system integrates these inputs and produces the motor response necessary to maintain balance.[13] Therefore, any subtle changes in a person's ability to maintain upright balance can be used to indirectly assess the status of the person's neurological system. For example, if the neurological system is altered due to physiological stress, such as heat stress, that can potentially alter the neurological system, or biomechanical stress, such as additional weight due to equipment, that can potentially alter motor outputs, these changes can be detected using postural balance measurement techniques. Therefore, postural balance is an indirect measure of the effect of both physiological and biomechanical stress on a worker and can be an outcome measure of the worker's overall safety status. Postural instability can be hazardous in the workplace due to the increased risk of slips/falls or other accidents.

The maintenance of upright balance in an occupational setting is essential for the worker to perform job tasks efficiently and safely. Variables have been developed to estimate the severity of postural stability during task performance and could be applied as a safety monitoring technique for workers wearing PPE.[14] Some studies have shown that an increase in body sway is associated with an increased risk of falling in the elderly.[15–18]

Postural stability can be measured noninvasively and can be accomplished with simple tests. Other traditional methods of assessing the impact of workloads and the PPE worn may not be sufficient to determine a worker's postural stability. Heart rate and perceived exertion alone, although shown to increase linearly with workloads, does not predict postural stability.[19] This study investigated the use of postural sway measurements as a potential safety monitoring technique on a worker wearing PPE. Specifically, this study examined postural sway, heart rate, and subjective ratings to determine the potential neurophysiological strain associated with various levels of PPE and two workloads.

METHODS

For this study, two testing sites, the USEPA Training Center and the International Chemical Workers Union (ICWU) Training Center, both located in Cincinnati, Ohio, were used. Sixteen volunteer participants for this study were recruited from training and fire fighting personnel at the EPA Training Center, the ICWU Training Center, and the hazardous response/fire division of the City of Cincinnati fire department. The sample size (80% power; $\alpha = 0.05$) was determined from a previous study.[20] Each subject was screened by an occupational medicine resident to ensure he or she was healthy, with no falls in the past year and no history of ocular pathology, musculoskeletal disorders, chronic back pain, dizziness, tremors, alcoholism, vestibular disorders, neurological disorders, diabetes, or cardiopulmonary disorders. Each subject signed a consent form and was given study guidelines before the test session. The postural sway testing method and experimental procedures followed a protocol approved by the University of Cincinnati Institutional Review Board.[21]

Prior to testing, each subject completed a health and work history questionnaire. This questionnaire gathered information on age, sex, race, weekly consumption of alcohol, daily consumption of caffeine and nicotine, and any drug use. Information on PPE use was also obtained from this questionnaire. On the day of the testing, each subject also completed a session interview. The session interview collected information on recent (12 hours prior to testing) history of sleep; meals; injuries; medication; work; and caffeine, nicotine, and alcohol intake. Physical measurements of height, shoulder height, knee height, weight, foot length, and foot width were collected for each subject at the time of the testing session.

The PPE worn for this study included equipment for levels A, B, and C. Equipment was loaned by the USEPA and ICWU training centers and consisted of equipment used for training at these sites. The level A worn for this study included a supplied air respirator, a fully encapsulating suit, chemically resistant protective boots, inner gloves, and chemically resistant gloves. The level B worn included a supplied air respirator, a chemically resistant splash suit, chemically resistant protective boots, and chemically resistant gloves. The level C worn included an air-purifying respirator, a chemically resistant splash suit, chemically resistant protective boots, and chemically resistant gloves.

The supplied air respirators had full face masks with tanks supported on the back with shoulder straps. The air purifying respirators were full face respirators and various types were worn with high-efficiency particulate air (HEPA) cartridges. The fully encapsulating suit worn was an EPA training suit made with polyvinyl chloride (PVC). The chemically resistant splash suits were made up of a pair of pants and a jacket made with PVC. The level A and B suit ensembles weighed 36.6 ± 1.2 lbs and 29.3 ± 1.5 lbs at the EPA site and 47.2 ± 1.1 lbs and 39.3 ± 0.6 lbs at the ICWU site, respectively. The level C ensemble weighed 8.8 ± 1.4 lbs at both sites. The levels A and B weighed more at the ICWU site because a larger tank was used for the SCBA.

While wearing the three levels of PPE, the subject performed a resting and workload task. The resting task assumed no postural muscle fatigue and required the subject to sit quietly in a chair for five minutes. To expose the postural muscles in the legs to a workload and to potentially fatigue these muscles, the person maintained a static semi-squat position for as long as possible with a maximum squatting time of five minutes. The amount of time that a subject could voluntarily maintain the semi-squat position, which is until he or she experienced excessive discomfort in his postural muscles, was recorded as the workload exposure time. The subject's semi-squatting position was defined by a working surface height equal to 50 percent of the subject's shoulder height and a working distance equal to the subject's maximum reach.(21) While maintaining this position, the subject completed the two-handed standardized task on the Minnesota Manipulation Board (Lafayette Instruments, Lafayette, Indiana).(22)

The instrument used to quantify changes in postural stability is a microprocessor-based force platform system. This system is able to quantitatively measure human body sway noninvasively. The portable system utilizes a force platform and computer. The force platform is an Advanced Mechanical Technology, Inc. (AMTI) AccuSway system and was used with a Laser 386SX/3 personal computer with AccuSway "Swaywin" software.

The force platform is equipped with "hall effect" sensors and a built in microprocessor that measures three forces along the three orthogonal axes, Fx, Fy, and Fz, and the three moments around the three axes, Mx, My, and Mz. Data were collected at a 50 Hz sampling rate and were transferred through the serial port interface at 9600 baud. The output of the three forces and three moments was used to calculate the x and y coordinates of the movement of the center of pressure (CP) corresponding to body sway.(23) The location of the CP approximately coincides with that of the CG during a static task.(24) The movement of CP has been used for quantifying postural stability in previous research studies.(19,20,22,23,25–28) The area and length of the CP sway pattern, obtained from the x-y plots, were used to characterize the postural sway. The total area of sway (SA) is the area enclosed within the outer perimeter of a stabilogram plot and is measured in square centimeters (cm^2). An increased sway area implies to an increased risk of postural instability since the person's center of pressure is closer to their stability boundary. The total sway length (SL) is the length of the path traversed by the sway pattern and is measured in centimeters (cm). An increased sway length implies increased muscular activity to maintain balance.

For the sway tests, each subject stood on the platform with his or her feet in a comfortable position. This foot placement was traced on an acetate cover on the force platform. The subject stood in the same position for each test. The tests were as follows:

- Eyes Open on Plate (EO): The subject stood quietly on the platform with his or her eyes open. All the sensory information inputs—visual, vestibular, and somatosensory—are unaltered and available for this test.
- Eyes Closed on Foam (FC): The subject stood quietly on a four-inch-thick foam pad placed on top of the platform with his or her eyes closed. This test removes the visual input and alters the somatosensory input, leaving the vestibular system with primary control over balance.
- Reach (RE): The subject stood quietly on the platform for eight seconds. On command, he or she lifted a five-pound weight from a shelf placed at knee height in front of him or her to chest level. This sequence was repeated four times, then the subject stood quietly for the remainder of the 30 seconds. This test evaluates the maintenance of balance during task performance.

The above protocol is designed to utilize postural sway as an indirect assessment of the effect of various stressors on the central nervous system (CNS). It indirectly assesses the visual, vestibular, and somatosensory inputs and their effects on maintaining postural balance.(23) For each sway measurement, a series of three 30-second sway tests were performed in random order. The random order was generated using a random number generator, the RANUNI function, available as part of the Statistical Analysis Software (SAS) software.(30)

The method used to quantify physiological strain was a real-time heart rate monitor, Polar Vantage XL Heart Monitor Data Logger (Model #45900, Polar USA, Inc., Stamford, CT). The transmitter was secured with an elastic band around the subject's chest underneath all layers of clothing. The receiver was attached on the outside of the clothing and secured with tape. The heart rate was monitored continuously throughout the testing session. Intervals were marked on the data logger to indicate when the various levels of PPE were donned and when the resting and workload task began and ended.

The heart rate (HR) was averaged between these beginning and ending marks to determine the HR during the task. A calculation of percent maximum HR can indicate the physical strain due to the PPE and workload. The percent maximum HR is closely related to the percent of maximum aerobic capacity or maximum oxygen consumption (VO_2 max) of a person during moderate to heavy whole body work. The average HR during the task, resting HR, and maximum HR were used to calculate the percent maximum HR. The resting HR was obtained by averaging seven readings taken every two minutes while the subject sat quietly at the beginning of the session. The maximum HR was obtained by subtracting the subject's age from 220.(30)

The natural wet-bulb, dry-bulb, and globe temperatures were measured along with the wet-bulb globe temperature (WBGT) index using the Heat Stress computer (model #858, Vista Scientific Corp., Ivyland, PA—company is no longer operational). Measurements were recorded at the beginning and end of each testing session. Correction factors for PPE were added to the mean of the two measurements to estimate the heat stress in each PPE level. A correction factor of 11 was added for level A and 8 for levels B and C to adjust the ambient WBGT to the estimated WBGT inside the protective clothing as per Bernard.(31)

Subjects were asked their perceived exertion (PE) level using Borg's Self-Rating Scale,(32) which ranges from 6, which is "very, very light" PE, to 20, which is "very, very hard" PE.

They were also asked to rank bodily discomfort using a modified Bishop-Corlett diagram.[33] They ranked their neck, upper back, mid to lower back, buttocks, thighs, knees, and lower legs/feet on a scale from 0, meaning "no discomfort," to 3, meaning "extremely uncomfortable."

Experimental Procedure

Each subject was tested in one session lasting approximately three hours. The session began with anthropometric measurements and placement of the heart rate monitor. A resting heart rate was obtained and baseline postural sway measurements with no PPE, level A, level B, and level C were completed. The subject donned the three levels of PPE, levels A, B, and C, in random order. After completing the baseline sway measurements, the subject completed the two tasks, resting and workload, in random order. The subject did not complete the two tasks with no PPE on, only with levels A, B, and C donned. Another set of sway measurements was completed after each task. After the workload task, subjective measurements were also recorded. The subject was allowed to rest and drink water between tasks, as needed. If the subject wanted to remove any equipment at this time, he was allowed to do so.

Data Analysis

An analysis of covariance (ANCOVA) using backward elimination of insignificant covariates was used to determine the effect of PPE level, task, and the PPE and task interaction on the postural sway variables. The same analysis was also completed for percent maximum HR and PE. The SAS procedure PROC MIXED was used for the analysis of these variables.

SA and SL were the dependent variables used to quantify postural sway. Both SA and SL were transformed to their natural logarithm for the statistical analysis. The three test conditions, EO, FC, and RE, were tested independently. The independent variables used were PPE level (A, B, or C), task (rest or workload), testing site (SITE), WBGT (°C), age (years), weight (kg)-to-height (cm) ratio (WTHT), workload exposure time (F_TIME), alcohol consumption (number of 12-ounce beer equivalent drinks per week), caffeine consumption (number of 8-ounce drinks per day), and smoking (cigarettes per day). The interaction of PPE and task (PPE*task) was also included.

Selection of the testing site as a variable was due to a concern that the surroundings and different weights of the equipment might be an important factor. Selection of the age, WTHT, alcohol, caffeine, and smoking covariates was based on the significance demonstrated in previous studies.[19,20,25,26] WTHT was used in place of height and weight individually since these variables have been highly correlated in previous studies.[27] Fatigue time was included to account for any effects it might have on the dependent variables.

The backward elimination strategy methodically drops the covariates with the least predictive power. All variables with a p value > 0.05 were eliminated one at a time from the model, with the variables having the greatest p values dropped first. The variables that remained after this process were identified as cofactors in the regression model. Since the HR and PE were expected, by hypothesis, to increase with the increasing levels of protection, a one-tailed test with alpha $= 0.05$ was used to judge statistical significance. A one-tailed test was also used for the PPE baselines compared to the no-PPE baseline sway measurements and for the task variable. Otherwise, a two-tailed alpha $= 0.05$ was used. For the simple post hoc comparisons, a Dunn-Bonferroni correction factor resulted in an adjusted alpha $= 0.016$ comparisons among the levels of PPE, alpha $=$ 0.008 for the comparisons of the PPE baselines to the no-PPE baseline data and an adjusted alpha $= 0.0125$ for the interaction among the levels of PPE and task. The following was the initial ANCOVA model used for the outcome measures of the three test conditions for SA and SL and percent maximum heart rate:

$$\begin{aligned}\ln(\text{sway variable}) &\text{ or percent maximum HR}\\ &= b_0 + b_1(\text{PPE}) + b_2(\text{task}) + b_3(\text{site}) + b_4(\text{WBGT})\\ &\quad + b_5(\text{age}) + b_6(\text{WTHT}) + b_7(\text{F\_TIME}) + b_8(\text{alcohol})\\ &\quad + b_9(\text{caffeine}) + b_{10}(\text{smoking}) + b_{11}(\text{PPE}*\text{task})\end{aligned}$$

Since the perceived exertion (PE) was only taken after the workload task, the task and the interaction of task and PPE level were not estimable. The following initial model was used for the analysis of PE:

$$\begin{aligned}\text{PE} &= b_0 + b_1(\text{PPE}) + b_2(\text{site}) + b_3(\text{WBGT}) + b_4(\text{age})\\ &\quad + b_5(\text{WTHT}) + b_6(\text{F\_TIME}) + b_7(\text{alcohol})\\ &\quad + b_8(\text{caffeine}) + b_9(\text{smoking})\end{aligned}$$

For the discomfort data, the SAS procedure PROC LOGISTIC was used and the discomfort values higher than zero were grouped to provide a dichotomous response. The PPE level was dummy coded for the logistic regression analysis. Like the perceived exertion data, the discomfort ratings were only obtained after the fatiguing task, so task and the interaction of task and PPE level were not estimable. Each body part was analyzed separately. The following initial model was used to analyze the probability (prob.) of discomfort:

$$\begin{aligned}\text{Prob. }&(\text{body part discomfort})\\ &= b_0 + b_1(\text{A}) + b_2(\text{B}) + b_3(\text{site}) + b_4(\text{WBGT}) + b_5(\text{age})\\ &\quad + b_6(\text{WTHT}) + b_7(\text{F\_TIME}) + b_8(\text{alcohol})\\ &\quad + b_9(\text{caffeine}) + b_{10}(\text{smoking})\end{aligned}$$

A and B are the dummy coded levels of PPE, indicating that level A or level B was observed, respectively. To test the effect of the PPE on the sway variables independent of the task effect, the baseline sway measurements (BASE) were used as the dependent variables in the ANCOVA models in which the PPE levels were the independent variables:

$$\ln(\text{BASE}) = b_0 + b_1(\text{PPE})$$

Correlations were also calculated for heart rate and perceived exertion with SL and SA, and heart rate with perceived exertion and discomfort. The SAS procedure, PROC CORR, was used to obtain the Pearson correlation coefficients.

RESULTS

The demographic information for the subjects is provided in Table I. The corrected WBGT values for the testing sessions were 28°C ± 1.7°C for level A and 25°C ± 1.7°C for levels B and C. Mean values for the postural sway variables and heart rates are shown in Tables II and III, respectively.

For the baseline sway area (SA), the PPE levels produced significant differences ($p < 0.05$) for the EO test condition with level A producing a significantly greater SA (by 78%) than for no PPE ($p < 0.0125$). For the RE test condition, the PPE levels produced significant differences ($p < 0.05$) for the baseline SA. For the FC condition, no baseline SA for the PPE levels were significantly different from each other. For the baseline sway length (SL), the PPE levels were significantly different for the RE condition ($p < 0.05$). The PPE levels A, B, and C baselines for the RE test condition produced significantly larger SL (by 17%, 18%, and 19%, respectively) than the no-PPE baseline SL ($p < 0.0125$). No significant differences for the baseline SL response to the PPE levels for the EO and FC conditions were found. The linear regression models for the baseline sway measurements with significant results are shown in Table IV.

The PPE levels and tasks did not produce significantly different values for SA for any test condition. The task produced significantly different SL ($p < 0.05$) in all of the test conditions. The workload task increased the SL by 7 percent over the resting task SL for the EO test condition, 11 percent for the FC, and 2 percent for the RE. The mean SL values and one standard error limit for the task are shown in Figure 1.

TABLE I
Demographics for 16 subjects

Variable (units)	Mean	Standard deviation	Minimum	Maximum
Age (years)	41.80	9.30	20.92	56.33
Height (cm)	177.00	5.92	166.37	185.42
Weight (kg)	81.38	9.73	58.95	102.60
WTHT (kg/cm)	0.46	0.05	0.34	0.59
Smoke (cigarettes/day)	4.00	8.41	0.00	24.00
Alcohol (drinks/week)	2.09	2.23	0.00	7.00
Caffeine (drinks/day)	2.63	2.70	0.00	11.00
Knee height (cm)	50.17	2.92	45.72	54.61
Functional reach (cm)	66.98	3.23	60.96	71.12

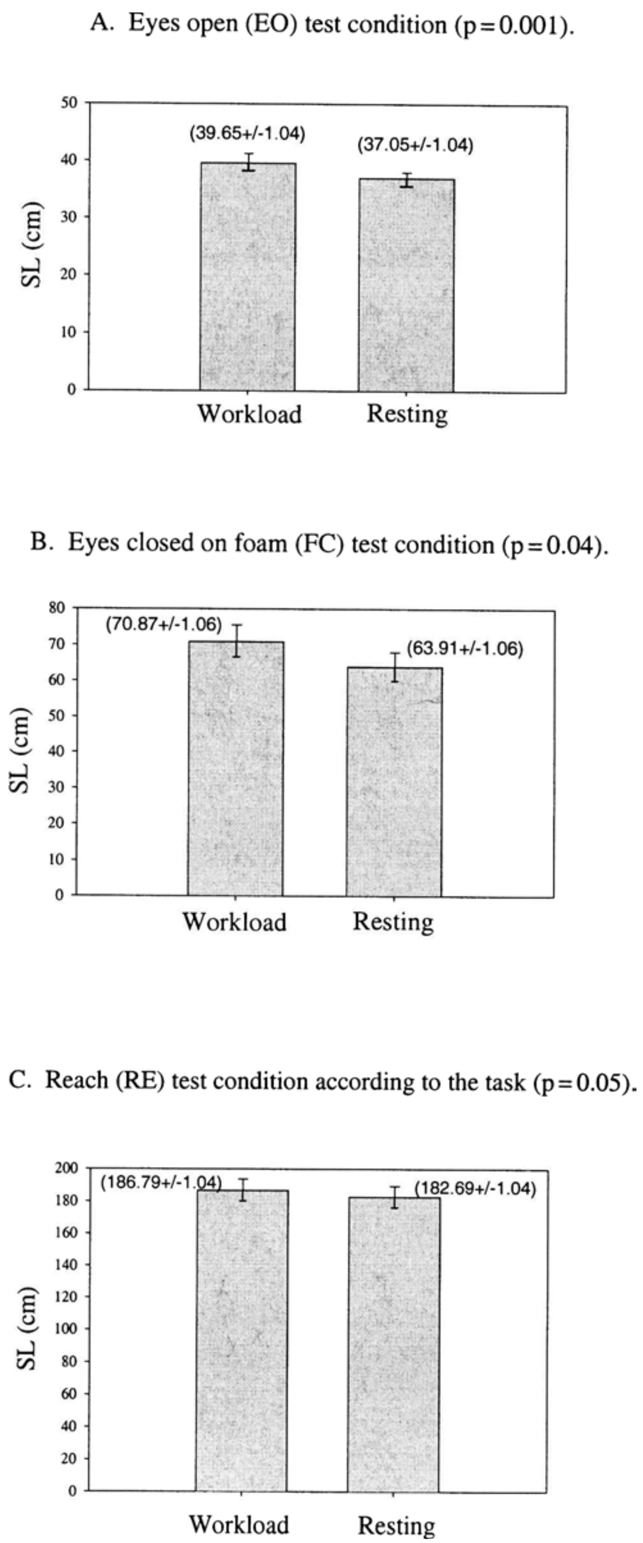

FIGURE 1
Sway lengths (SL) according to task for the eyes open, eyes closed on foam, and the reach test conditions (GM and one S.E. limit).

TABLE II
Arithmetic means ± standard deviation for sway area (SA) and sway length (SL) variables for each PPE level, task, and test condition (n = 16)

PPE level	Task	Test condition	SA ± S.E. (cm^2)	SL ± S.E. (cm)
None	None	EO	0.92 ± 0.48	33.52 ± 7.85
		FC	7.06 ± 3.96	78.08 ± 26.26
		RE	31.79 ± 15.11	166.86 ± 31.61
A	None	EO	1.98 ± 2.13	36.93 ± 10.81
		FC	5.69 ± 2.81	67.15 ± 20.56
		RE	36.06 ± 10.60	192.44 ± 22.22
	Resting	EO	1.59 ± 0.96	36.51 ± 7.23
		FC	4.47 ± 2.27	60.11 ± 19.05
		RE	32.83 ± 11.14	180.11 ± 18.14
	Workload	EO	1.40 ± 0.64	38.78 ± 7.00
		FC	6.16 ± 4.17	69.38 ± 19.72
		RE	32.78 ± 7.70	192.56 ± 18.60
B	None	EO	1.03 ± 0.36	35.43 ± 5.16
		FC	6.89 ± 4.34	79.51 ± 37.94
		RE	37.92 ± 13.79	195.25 ± 26.24
	Resting	EO	1.33 ± 0.54	37.92 ± 12.06
		FC	6.00 ± 2.99	72.55 ± 23.67
		RE	35.34 ± 14.40	187.23 ± 34.34
	Workload	EO	1.40 ± 0.73	41.25 ± 14.25
		FC[A]	9.31 ± 7.62	85.56 ± 31.60
		RE[A]	34.01 ± 11.11	188.51 ± 41.15
C	None	EO	1.16 ± 0.76	37.84 ± 7.27
		FC	5.95 ± 3.86	72.08 ± 24.20
		RE	36.75 ± 9.77	195.61 ± 24.86
	Resting	EO[A]	1.22 ± 0.49	38.80 ± 5.55
		FC	8.08 ± 8.85	66.78 ± 20.34
		RE	37.86 ± 11.91	187.04 ± 31.12
	Workload	EO	1.11 ± 0.52	42.08 ± 8.25
		FC	5.97 ± 3.70	71.72 ± 22.26
		RE	34.97 ± 10.28	187.85 ± 33.36

[A]n = 15 for these conditions due to equipment failure during testing.

TABLE III
Mean ± standard deviation for heart rates and peak heart rates during the baseline resting and the resting and workload tasks for each PPE level (n = 16)

PPE level	Condition	Mean heart rate ± s.d.	Peak heart rate ± s.d.
None	Baseline resting	77.54 ± 10.25	84.44 ± 10.39
A	Resting	83.31 ± 11.26	93.43 ± 11.89
	Workload	107.47 ± 11.11	120.56 ± 10.15
B	Resting	80.44 ± 10.27	89.19 ± 9.38
	Workload	105.47 ± 12.20	117.63 ± 14.72
C	Resting	83.13 ± 9.84	91.50 ± 9.56
	Workload	104.50 ± 9.42	116.50 ± 12.28

TABLE IV
Linear regression models for the baseline measurements of sway area (SA) and sway length (SL) for significant conditions only (one-tailed $\alpha = 0.05$)

Dependent variable			Independent variable	p value
SA	EO	PPE baseline		0.027
			difference between level A and no PPE	0.004[A]
SA	RE	PPE baseline		0.029
SL	FC	PPE baseline		0.001
			difference between level A and no PPE	0.001[A]
			difference between level B and no PPE	0.001[A]
			difference between level C and no PPE	0.001[A]

[A]These were post hoc comparisons tested at $\alpha = 0.013$.

For the FC test condition, the PPE levels produced significantly different SL ($p < 0.008$). SL while wearing level B was 18 percent longer than while wearing level A PPE. For the RE test condition the interaction of PPE level and task ($p < 0.03$) produced significantly different SL. The level A SL during the workload condition also was significantly longer (by 7%) than the level A resting SL ($p < 0.001$). The mean SL values and one standard error limit for the PPE levels for the FC test condition and the interaction of PPE levels and tasks for the RE test condition are shown in Figure 2. The linear regression models relating SL to PPE level and task are shown in Table V.

The task significantly affected the percent maximum heart rate ($p < 0.0001$). The arithmetic mean HR for 16 subjects was 82 beats per minute (bpm) or 4.78 percent of the maximum HR during the resting task, and 106 bpm or 28.15 percent of maximum HR for the workload task. The HR results for the workload task indicate that a moderate effort was exerted.[30] The differences in heart rates between the three PPE levels were not statistically significant and no significant correlations were found between heart rate and the SA or SL for any test condition. The linear regression model relating percent maximum HR to the PPE levels and task are shown in Table V.

The PPE level, WBGT, and workload exposure time were statistically significant ($p < 0.05$) for the response of perceived exertion. The perceived exertion increased 12 percent and 8 percent for the subjects wearing PPE levels A and B, respectively, as compared to level C; however, only level A was significantly higher than level C. These results are shown in Figure 3. The perceived exertion was not significantly correlated with SL or SA for any test condition. The perceived exertion was marginally correlated ($p < 0.05$) with heart rate for the level B PPE, but not the level A or C PPE. The perceived exertion was also significantly correlated ($p < 0.05$) with the workload task. The linear regression models relating PE and PPE levels and task are shown in Table V.

For the neck, buttocks, knees, and lower legs, no significant differences in the probability of discomfort were found among the PPE levels. For the upper back, lower back, and thighs, the probability of a discomfort response while wearing level A PPE was significantly higher than while wearing level B or C PPE. For all the body parts, the odds ratio for experiencing discomfort in the level A PPE condition was greater than 1.0. For the neck, the odds ratio was greater than 1.0 for the level

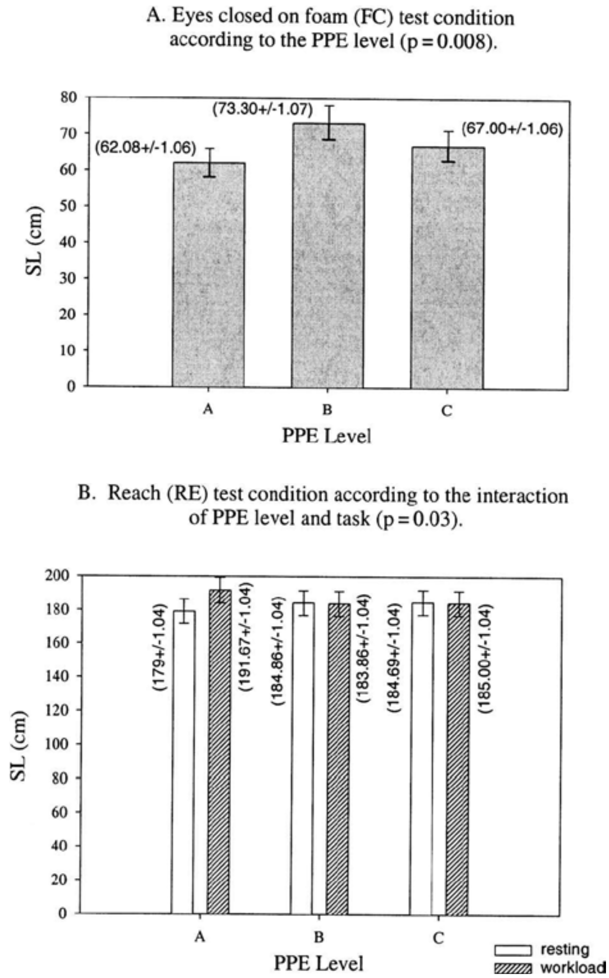

FIGURE 2
Sway lengths according to PPE and the interaction of PPE and task (GM and one S.E. limit).

TABLE V
Linear regression models for relating sway length (SL), percent maximum heart rate, and perceived exertion to level of PPE (two-tailed $\alpha = 0.05$) and workload task (one-tailed $\alpha = 0.05$) for significant conditions only

Dependent variable		Independent variable		p value
SL	EO	PPE		0.17
		TASK		0.001
		SMOKE		0.02
SL	FC	PPE		0.008
			difference between level A and level B	0.002[A]
		TASK		0.04
		BASE		0.01
SL	RE	PPE		0.97
		TASK		0.05
		PPE*TASK		0.03
			difference between level A*workload and level A*resting	0.002[B]
% max	HR	PPE		0.28
		TASK		0.0001
PE		PPE		0.004
			difference between level A and level C	0.0001[A]
		WBGT		0.03
		F_TIME		0.0001

[A]These were a post hoc comparison tested at $\alpha = 0.017$.
[B]This was a post hoc comparison tested at $\alpha = 0.008$.

B PPE condition. A diagram of the percent reported discomfort among the subjects for each body part and each PPE level is provided in Figure 4. Discomfort was not related with any PPE level, but was significantly related ($p < 0.05$) with the workload task.

DISCUSSION

Monitoring worker safety is essential, especially in working environments that require the use of PPE. Maintaining postural balance is essential for a worker to carry out any task or job safely. Akbar-Khanzadeh and Rejent[35] found that slips/falls accounted for 14 percent of injury/illness cases in a hazardous waste cleanup company, which was the third highest incidence rate behind being struck by (18%) and strained by (16%) a mechanical hazard.

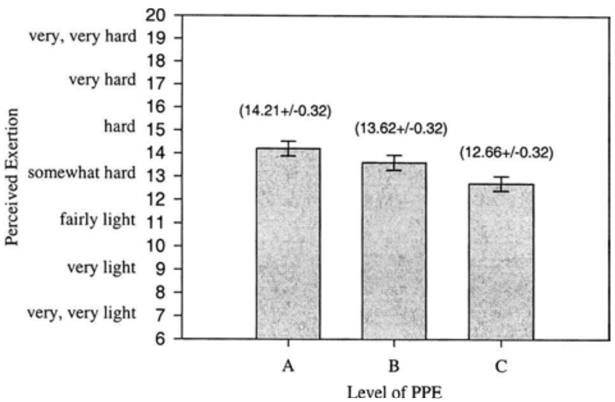

FIGURE 3
The perceived exertion level for subjects wearing the three levels of PPE. (AM and one S.E. limit)

Traditional measurements taken in the field to assess physical risk factors, such as workload and heat stress, may not reflect the neurophysiological status of an individual worker. Environmental measures are simple to collect in the field but are, at best, estimates, particularly after adjusting for clothing ensembles and workload. Sweat rate and core temperature can be used to evaluate physiological heat strain but are not practical to measure in the field.[3] Since postural balance is a result of a complex interaction of physiological inputs and motor outputs, it can be used as an indirect indicator of a person's neurophysiological status. Postural stability measurements can quantitate changes in this status. An increase in the postural sway measurements of SL and SA implies an increase in postural instability.

Heart rate is another physiological measure of heat strain that can be collected in the field, but was not correlated with postural stability, or SL and SA, in this study or in a previous study.[19] The mean percent maximum heart rate, in this study, reached 28 percent, which does not exceed the guideline of 33 percent, the level at which the average worker is likely to fatigue. Perhaps a higher mean percent maximum heart rate would have a

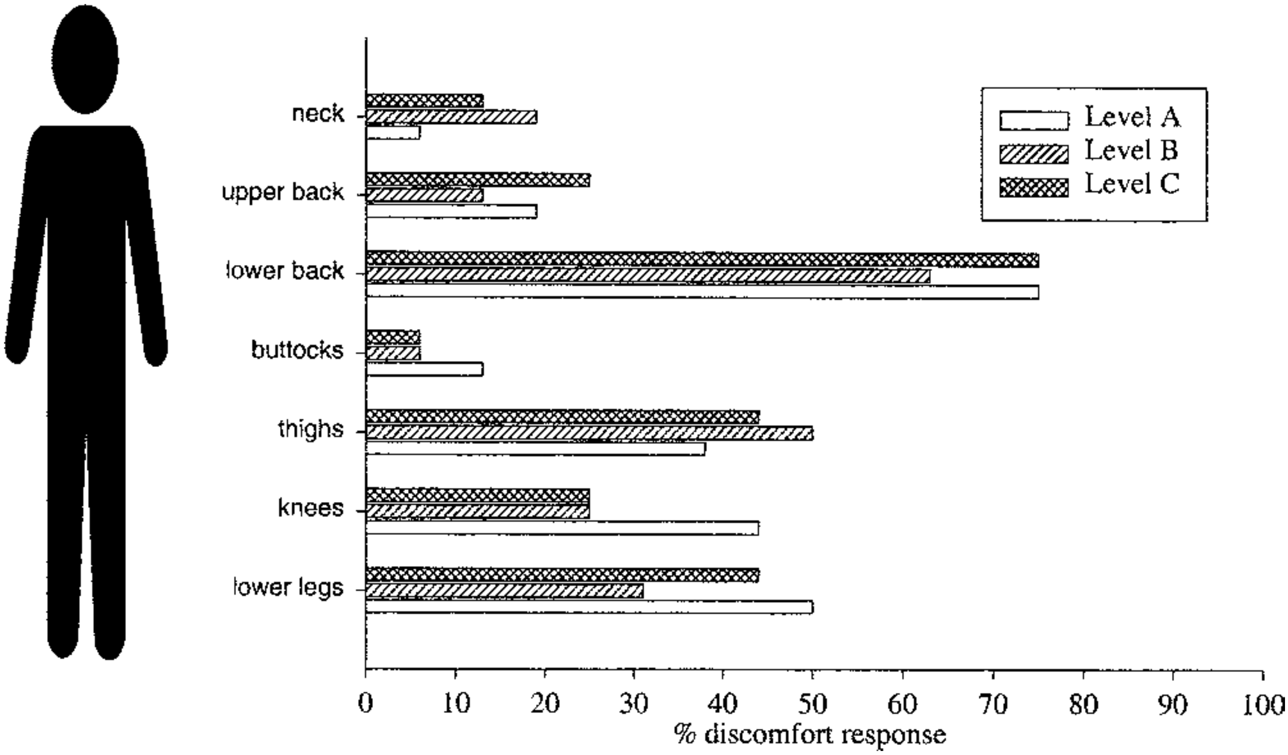

FIGURE 4
Percent discomfort response of subjects after the workload task.

significant effect on the postural balance measures.(31) The results from this study also demonstrate heart rate did not change with the levels of PPE, indicating no difference in effort level due to wearing the PPE; yet significant differences were found for the postural sway measurements due to wearing PPE. This indicates that heart rate does not appear to be an indicator of postural stability while wearing PPE.

Perceived exertion did increase with the increased levels of PPE. In this study, perceived exertion was not correlated with the sway variables, suggesting that subjective measures of whole body exertion also do not correspond to changes in postural stability for workers wearing PPE. The self-reported discomfort in the upper back, lower back, and thighs was significantly higher when the subjects wore the level A PPE. The odds ratios while wearing PPE level A for reporting discomfort in the upper back, lower back, and thighs were 283.98, 387.36, and 73.52, respectively. This demonstrates that wearing the level A equipment while performing a task in the semi-squat position is very likely to cause discomfort in these body parts. This is possibly due to the level A PPE weighing the most and causing a heavier burden on the subject.

Of the postural sway measurements, the SL response is an indirect indicator of the muscular activity elicited for maintaining balance. For all three test conditions, EO, FC, and RE, the task effect produced significantly different SL responses, with the workload task increasing the SL. These results suggest that a person with fatigued postural muscles due to exposure to a certain workload (sustained squatting) requires increased muscular activity to maintain balance.

The FC test condition removes the visual input and alters somatosensory information, making it a more challenging condition for maintaining balance. The vestibular system, which is controlled by the higher centers of the central nervous system, is heavily relied on for this test.(22,27,28,36) Since regulation of body temperature is also controlled in the higher centers of the brain, the hypothalamus specifically,(37) this test condition may be more sensitive to indicating the influence of heat stress on the subject's postural instability. The SL response for subjects wearing the B level PPE was significantly higher than level A in this test condition. Further investigation of this result is necessary, but a possible explanation could be that because the heat stress levels were estimated (the ambient WBGT values were adjusted by a correction factor), a distortion of the actual heat stress may have occurred. Personal WBGT measurements were not taken.

There are reports in the literature that suggest that heat stress levels should be the highest in a fully encapsulating suit (level A).(1,4,6–9) Since the equipment used for this study was training equipment, the level A fully encapsulating suits were not certified as impermeable. The level B and C suits may have had a higher heat stress level than level A, since the equipment was worn for such a short period of time. The protective clothing worn for levels B and C were placed directly against the skin, while the level A fully encapsulating suit provided some

TABLE VI
Final logistic regression model for bodily part discomfort

Body part	Independent variable	p	Odds ratio	Relative risk ratio
Neck				
	A	0.53	2.598	
	B	0.59	1.790	
	WBGT	0.02		0.542
Upper back				
	A	0.03	283.971	
	B	0.25	0.231	
	WBGT	0.009		0.121
	Age	0.03		0.806
	Caffeine	0.03		0.457
	Smoking	0.01		1.426
Lower back				
	A	0.02	387.355	
	B	0.33	0.373	
	WBGT	0.01		0.137
	WTHT	0.02		0.001
	Alcohol	0.02		0.445
Buttocks				
	A	0.55	2.143	
	B	1.0	1.000	
Thighs				
	A	0.01	73.418	
	B	0.99	1.000	
	WBGT	0.0005		0.220
	Age	0.009		0.801
	Caffeine	0.02		0.532
	Workload time	0.02		0.981
Knees				
	A	0.27	2.378	
	B	1.0	1.000	
	Age	0.03		1.129
Lower legs				
	A	0.72	1.286	
	B	0.47	0.584	

air space between the skin and the suit. Since the subjects spent only approximately eight minutes in each PPE, completing a resting or workload task and the sway tests, the microenvironment inside the fully encapsulating suit may not have become saturated and allowed some cooling due to the evaporation of sweat. If the protective suits were worn longer, this microenvironment in level A may have potentially become saturated and not allowed this cooling effect.

For the RE testing condition, all sensory inputs are available but a dynamic task is performed. The SL response for the interaction of wearing the various PPE levels and the fatiguing task was statistically significant. The level A workload SL response was significantly longer (7%) than the level A resting response. Neither level B nor C responses were significantly different from the average difference between the fatigue and resting task (2%). This indicates that level A in conjunction with the fatiguing task increased muscular activity to the greatest extent. This could be due to the weight difference and decreased dexterity associated with level A PPE. The level A weight was 7.6 lbs and 32.9 lbs heavier, on average, than the level B and C equipment, respectively.

CONCLUSIONS

These results indicate that there is a difference in postural stability in workers wearing different levels of protective equipment while having fatigued postural muscles. In particular, the sway length response was sensitive enough to detect changes in postural stability due to fatigued postural muscles while wearing PPE. The sway test condition of eyes closed on the foam is potentially the best indicator of heat stress of the three sway tests performed in this study. This test requires the subject to rely on higher centers of the brain, which may be the most altered under heat strain. Further investigation into the effect of the weight and dimensions of the PPE on postural balance needs to be completed. The technique of measuring postural sway, as a safety monitoring technique for workers wearing PPE, could be further developed as a potentially effective and reliable technique.

RECOMMENDATIONS

Further investigation into the various components, such as the effect of physiological stress and biomechanical stress, that would lead to the detected postural stability changes should be undertaken. Conducting this study with standard equipment that is in use in the field and in an environment where the heat stress could be more closely monitored would provide a better model of the effect of heat stress on postural stability. Also, a study in the field would provide further insight into whether postural sway testing may be potentially used as a safety monitoring technique.

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