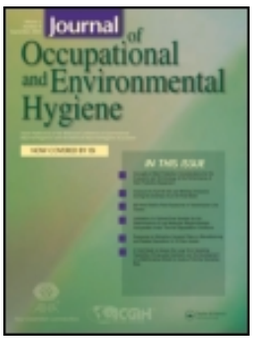

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Suspension Tolerance in a Full-Body Safety Harness, and a Prototype Harness Accessory

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Workers wearing full-body safety harnesses are at risk for suspension trauma if they are not rescued in 5 to 30 min after a successfully arrested fall. Suspension trauma, which may be fatal, occurs when a person's legs are immobile in a vertical posture, leading to the pooling of blood in the legs, pelvis, and abdomen, and the reduction of return blood flow to the heart and brain. To measure suspension tolerance time, 22 men and 18 women with construction experience were suspended from the chest D-ring (CHEST) and back D-ring (BACK) of full-body, fall-arrest harnesses. Fifteen men and 13 women from the original group of subjects were then suspended using a newly developed National Institute for Occupational Safety and Health harness accessory (ACCESS), which supports the upper legs. Midthigh circumference changes were 1.4 and 1.9 cm, changes in minute ventilation were 1.2 and 1.5 L/min, changes in heart rate (HR) were 15.1 and 21.6 bpm, and changes in mean arterial pressure were 5.1 and −2.6 mmHg ($p \leq 0.05$) for all subjects during CHEST and BACK, respectively. Kaplan-Meier median suspension time for all subjects for the CHEST condition was 29 min (range 4–60 min) and 31 min (range 5–56 min) for the BACK condition. The 95th percentile for suspension time was 7 min for CHEST and 11 min for BACK. Cox regression revealed that body weight had a statistically significant effect on the time until experiencing a medical end point ($p \leq 0.05$) during the BACK condition. Mean (±SD) suspension time was 58 ± 6 min (range 39–60 min) for all subjects for the ACCESS condition. There were no terminations due to medical symptoms during the ACCESS suspension, changes in physiological variables were small, and 85% of ACCESS subjects completed 60-min suspensions. These data provide information on motionless suspension tolerance time to standards-setting organizations and demonstrate the potential of a prototype harness accessory to delay or prevent suspension trauma.

Keywords orthostatic intolerance, safety harness, suspension trauma

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The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of company names or products does not imply endorsement by the National Institute for Occupational Safety and Health.

INTRODUCTION

Full-body harnesses for fall arrest became the standard body support component of a personal fall arrest system in the United States in 1990, and in 1998, the Occupational Safety and Health Administration (OSHA) mandated harnesses for use in fall arrest for the U.S. construction industry.[1] This requirement has resulted in an increase in the use of full-body safety harnesses for fall protection. Once a worker's fall has been arrested by a full-body safety harness, the suspended worker must be rescued promptly. If a suspended worker is unconscious or immobilized due to injury, a potentially fatal condition known as suspension trauma may develop in 5 to 30 min.

Suspension trauma is the safety professional's term for the well-documented physiological phenomenon of orthostatic incompetence.[2,3] Very few occupational cases of suspension trauma have been reported; therefore, the actual scale of this occupational problem is unknown**.** Suspension trauma occurs when a person is suspended vertically and is motionless, causing the pooling of blood in the legs and other gravitationally dependent regions and the reduction of return blood flow to the heart. Most physiology-based investigations of orthostatic incompetence employ a tilt-table rather than whole-body suspension to induce symptoms.[4] Several studies have investigated the tolerance of human subjects to motionless suspension while wearing full-body safety harnesses.[2,5] The majority of subjects tested in four separate studies were men (approximately 9 women and 39 men). The range in motionless suspension duration for nine different full-body harnesses was 3.5 to 60 min. Approximately half the tests in these studies were terminated voluntarily by the test subjects, possibly due to discomfort caused by poor harness fit.

Safety harness standards have different requirements for full-body attachment points. American and Canadian standards allow only a back attachment, whereas international and European standards allow both front and back attachments.[2] Only one small study (six men and four women) investigated motionless suspension time with chest vs. back attachment points and found mean durations of 19 and 23 min for the chest and back attachment points, respectively.[2] Tests in that

study were terminated when subjects reported unbearable pain or when presyncope symptoms were reported, observed, or measured.[2]

A study by Madsen et al.[4] demonstrated that eight men and one woman tolerated motionless suspension with a chest strap and an additional strap supporting their knees for 58.9 min, a time that is more than double that reported in most suspension studies. The current study was conducted to provide more data on men and women's tolerance to motionless suspension in well-fitting, full-body safety harnesses, on tolerance with chest vs. back attachment points, and on the potential ability of a National Institute for Occupational Safety and Health (NIOSH)-developed prototype harness accessory to reduce or prevent suspension trauma.

METHODS

Sample size calculations (2-sided t-test) determined that a sample of 34 subjects would be adequate to detect a difference of 6 min in suspension time or 10 mmHg in mean arterial pressure (MAP) with a power of 0.80 ($\alpha = 0.05$). Institutional review board approval, including informed consent, was obtained prior to any human subject testing. The MSA TechnaCurv Tower Harness (Pittsburgh, Pa.) with a pullover design was used for suspension tests. The harness had padding on the shoulder and leg straps and a padded waist belt. Harness fit was evaluated based on the location of shoulder straps, chest D-ring, hip rings, and back D-ring (according to the harness manufacturer's instructions). Fit was evaluated with the subject standing, prior to suspension and prior to the addition of the harness accessory. If the chest D-ring was between 2 and 4 inches above or below the center of the sternum, or if the back D-ring was between 2 and 4 inches above or below the midpoint between the shoulder blades, the fit was determined to be "fair." D-ring locations less than 2 inches from their respective landmarks were deemed to be "good," and D-ring locations greater than 4 inches above or below their landmarks were deemed "poor."

The order in which each subject performed the chest D-ring (CHEST) and back D-ring (BACK) attachment tests was randomly assigned. Accessory tests (ACCESS) were conducted during a 4-week period after completion of all CHEST and BACK tests using 26 of the original subjects. For CHEST and BACK suspension tests, measurement of suspension time commenced after standing subjects were raised 2 inches from the floor. Subjects were raised from a seated position during the ACCESS tests. The accessory was designed to raise the upper legs to a horizontal position and to deploy passively, in order to be effective when a suspended worker is seriously injured or unconscious.

All subjects were asked to remain motionless for as long as they could during suspension tests. They were instructed that they could terminate the suspension at any time without penalty or loss of further participation in the study. Heart rate (HR), ECG, and pulse oximetry were continuously monitored, and blood pressure (BP) was measured automatically every 2 min at heart level by a Dinamap Pro 1000V3 monitor (GE, Milwaukee, Wis.). Blood pressure was also measured during the last minute of suspension. Thigh circumference was measured with a measuring tape during the first minute of suspension and every 10 min thereafter. Minute ventilation was continuously measured by a VivoMetrics LifeShirt (Ventura, Calif.) throughout the suspension period. The LifeShirt was calibrated for each subject before each test according to the manufacturer's instructions using 500-mL breathing bags.

The suspension was terminated if suspension duration reached 60 min. Medical test termination criteria included any of the following signs of orthostatic intolerance: (1) a systolic BP decrease of more than 20 mmHg as compared with the pretest value, (2) a diastolic BP decrease of more than 10 mmHg as compared with the pretest value, (3) a HR increase of more than 28 bpm over pretest value, (4) a HR decrease of more than 10 bpm from baseline, or (5) a pulse pressure decrease to less than 18 mmHg.[6] In addition, tests were medically terminated if any of the following signs or symptoms were reported or observed: shortness of breath, nausea, dizziness, and diastolic BP > 100 mmHg. Tests terminated due to extreme subject discomfort were reported as voluntary terminations.

The mean changes in physiological variables were analyzed for the effects of gender, body weight, and attachment point using a mixed model repeated measures analysis of variance (SAS Institute, Cary, N.C.) on the combined medically and voluntarily terminated (M + V) CHEST and BACK test data. Suspension durations for the CHEST and BACK tests were analyzed separately using a Kaplan-Meier survival analysis, and the effects of gender, height, and body weight on suspension duration were determined separately for CHEST and BACK tests using a Cox regression model (R: a language and environment for statistical computing, Vienna, Austria; version 2.4.1).

RESULTS

Twenty-two men (age 34 ± 8 years, weight 80.1 ± 14.1 kg, and height 178.0 m $\pm$ 7.5 cm, values are mean $\pm$ SD) and 18 women (age 34 ± 9 years, weight 66.7 ± 14.1 kg, and height 163.4 ± 4.5 cm, values are mean $\pm$ SD) weighing less than 300 lbs and between the ages of 18 and 45 participated in this study. All men and 14 women had previous or current construction experience. Four men and three women completed only one (not both) of the CHEST and BACK suspensions. The 15 men and 11 women who returned for the ACCESS tests had mean subject characteristics identical to the original group of subjects. The subjects who dropped out did so due to construction job constraints.

Figure 1 shows the typical postures for the CHEST, BACK, and ACCESS suspension tests. During BACK suspensions, the mean angle of the subjects' backs, measured using a Dejon Level/Inclinometer (Covington, Ohio), was 41° (range 28–57°) from vertical. Harness fit results and reasons for test termination are shown in Table I. Approximately 48% of

FIGURE 1. Typical postures for the CHEST, BACK, and ACCESS suspension tests. Mean back angle (from vertical) for the BACK suspension was 41°.

men had a fair harness fit before suspension, and 52% had a good fit. Forty percent of women had a poor fit, and 60% had a fair fit. For all CHEST and BACK suspension tests combined, approximately 75% of terminations were due to medical reasons, 23% were due to voluntary requests, and 1% was due to reaching the 60-min end point.

There were more voluntary terminations among men for the CHEST condition vs. BACK because of extreme rib discomfort in some subjects caused by the harness waist belt. Among the tests terminated for medical reasons, 25 were due to a decrease in either systolic or diastolic BP (Table II). A decrease in HR of $\geq$10 bpm was the cause of three terminations, and an HR increase of $\geq$28 bpm led to 20 terminations. Six women and one man experienced other medical signs and symptoms, including shortness of breath (2), nausea (1), dizziness (2), and diastolic BP $>$ 100 mmHg (3). Nineteen of 33 subjects who completed both CHEST and BACK suspensions had medical terminations for both conditions.

The mixed model analysis of variance applied to the M + V data revealed no differences due to gender in any physiological variables, including pretest-to-test-termination changes in thigh circumference, minute ventilation, HR, and MAP. Analysis of variance did demonstrate a significant relationship between body weight and change in MAP. During BACK suspensions, the pretest-to-test-termination change in MAP decreased (test-termination MAP decreased) as body weight increased ($p \leq 0.05$) for M + V. In addition, decreases in MAP were significantly greater ($p \leq 0.05$) with the BACK attachment point than CHEST for M + V. Table III shows separate mean changes in physiological variables for medically and voluntarily terminated tests. Changes were generally greater during medically terminated tests than during voluntary tests.

Table IV and Figure 2 depict the results of the Kaplan-Meier survival analysis used on the suspension duration data from CHEST and BACK suspension tests. The arithmetic mean ($\pm$ SD) suspension times were 24 $\pm$ 13 and 29 $\pm$ 12 min for CHEST and BACK suspensions, respectively, while medians were 28 and 31 min for CHEST and BACK, respectively. The 95th percentile suspension tolerance probability occurred at 7 min for CHEST and 11 min for BACK. The slopes of the CHEST and BACK suspension tolerance probability curves show that there is no threshold effect for suspension tolerance

TABLE I. Harness Fit and Reason for Test Termination

	Harness Fit			Reason for Termination		
Condition	Poor	Fair (% of tests)	Good	Medical	Voluntary (% of tests)	60 Min
Men						
CHEST (n = 20)	0	50	50	60	35	5
BACK (n = 20)	0	45	55	80	20	0
ACCESS (n = 15)	0	53	47	0	7	93
Women						
CHEST (n = 16)	37	63	0	81	19	0
BACK (n = 17)	41	59	0	82	18	0
ACCESS (n=11)	45	55	0	0	27	73

TABLE II. Number of Tests Terminated for ↓ Heart Rate, ↓ Blood Pressure, ↑ Heart Rate or Other Medical Reasons

	Number of Tests			
Condition	↓BP[A]	↓HR	↑HR	Other[B]
Men				
CHEST	5	2	4	1
BACK	9	0	7	0
Women				
CHEST	6	0	4	3
BACK	5	1	5	3

[A] ↓ in either systolic or diastolic.
[B] Other signs and symptoms included shortness of breath, nausea, dizziness, and diastolic blood pressure > 100 mmHg.

probability (Figure 2). There were one and nine subjects who experienced medical signs or symptoms within 5 and 15 min, respectively, during the CHEST suspension. One and six subjects experienced medical signs or symptoms within 5 and 15 min, respectively, during the BACK suspension.

Cox regression, applied separately for CHEST and BACK conditions, revealed that body weight (but not height or gender) had a statistically significant effect on the time until experiencing a medical end point ($p \leq 0.05$) during the BACK condition only. The hazard ratio estimate of 1.03 ($p \leq 0.05$), obtained from the Cox regression, indicates a 3% increase in risk of developing medical signs or symptoms for every 1 kg increase in body weight during BACK suspension. There were no significant effects of body weight, height, or gender during CHEST suspension.

The arithmetic mean suspension time for the ACCESS condition was 58 min, median was >60 min (medical symptoms, if they occur, would occur sometime after 60 min), and range was 39–60 min (Table IV). There were no terminations due to medical symptoms, changes in physiological variables were small, and 85% of ACCESS subjects completed 60-min suspensions.

TABLE IV. Descriptive and Kaplan-Meier Survival Analyses of Suspension Duration Data

	Arithmetic Mean[A]	Kaplan Meier Median	95th Percentile	Range
Condition	(min)	(min)	(min)	(min)
CHEST (n = 36)	24 ± 13	28	7	4–60
BACK (n = 37)	29 ± 12	31	11	5–56
ACCESS (n = 26)	58 ± 6	>60	—	39–60

[A] Mean (±SD).

DISCUSSION

Most prior motionless suspension tolerance research was conducted on young, healthy members of the military service.[5] The current study, conducted on healthy men and women with a mean age of 34 years, may be more applicable to the general population of construction workers (mean age 37.2 years).[7]

The current study found no effect of gender on suspension tolerance. An absence of gender differences in the ability to tolerate harness suspension has been reported elsewhere.[2] In general, harness fit was worse for women than for men in the current study, a finding that supports previous research.[8] Harness fit was assessed with subjects standing before being suspended and may not reflect fit during suspension.

In the majority of medically terminated CHEST and BACK tests, the reason for termination was either a decrease in BP or an increase in HR, or both. Both body weight and the BACK condition were related significantly to a decrease in MAP, findings that are supported by the results of the Cox analysis of BACK suspension times. Previous research has demonstrated that body weight, as well as height, shoulder width, and stomach girth, can help predict suspension tolerance.[2]

The Kaplan-Meier suspension tolerance probability curves (Figure 2) may be helpful in estimating minimum rescue times for suspended workers who are motionless. If rescue occurs in 31 min for a suspension with a back attachment point, 50% of workers may have experienced medical symptoms of

TABLE III. Mean (± SD) Physiological Changes for Medical and Voluntary Terminations

Condition	Change in Thigh Circumference (cm)	Change in Minute Ventilation (L/min)	Change in HR (bpm)	Change in MAP (mmHG)
Medical				
CHEST (n = 25)	1.7 ± 1.1	1.2 ± 1.8	15.8 ± 17.9	3.7 ± 21.6
BACK (n = 30)	2.0 ± 1.0	1.8 ± 2.1	23.7 ± 14.9	−5.1 ± 16.6
ACCESS	—	—	—	—
Voluntary				
CHEST (n = 11)	0.8 ± 1.1	1.0 ± 1.7	11.6 ± 10.9	9.3 ± 5.6
BACK (n = 7)	1.6 ± 0.4	0.4 ± 3.1	12.9 ± 5.5	7.9 ± 6.2
ACCESS (60 min, n = 22)	0.2 ± 1.0	0.8 ± 2.6	3.2 ± 7.1	5.2 ± 7.4
ACCESS (vol., n=4)	0.7 ± 0.3	0.4 ± 1.8	4.8 ± 9.7	2.3 ± 4.0

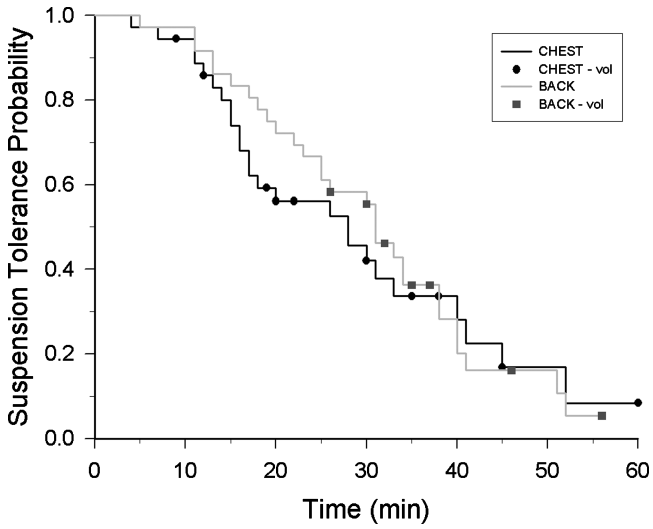

FIGURE 2. Kaplan-Meier suspension tolerance probability curves for the CHEST (n = 36) and BACK (n = 37) suspension tests. Symbols (■ and ●) depict voluntary terminations.

orthostatic intolerance. To ensure that no more than 5% of workers would experience symptoms, rescue would have to occur in 7 min for a chest attachment point and in 11 min for a back attachment point.

A major cause of orthostatic intolerance during vertical suspension is the pooling of blood in the veins of the upper legs and in the abdominal and pelvic regions. The support provided to the upper legs, as well as possible compression of the abdomen, by the prototype harness accessory prevented all medical signs and symptoms during 26 ACCESS suspensions. The 58-min mean suspension time attained during ACCESS tests is double the mean suspension times observed during CHEST and BACK and double the full-body harness suspension times reported in previous research.[2] Although four subjects terminated their suspensions early due to discomfort, there was no risk of medical symptoms, and 85% of subjects completed the 60-min suspension. The prototype harness accessory appears to be effective in preventing the medical signs and symptoms that are precursors to suspension trauma.

CONCLUSION

The current study confirms and expands the findings of previous investigations of suspension tolerance with full-body, fall-arrest safety harnesses. Median suspension times for CHEST and BACK attachment points were in the 25- to 30-min range observed elsewhere.[2] Body weight was confirmed as a significant predictor of suspension tolerance for the BACK suspension tests. The NIOSH-developed prototype harness accessory was shown to prevent the medical symptoms of orthostatic intolerance and to double the tolerable suspension time to 58 min. Future research should include dynamic fall-testing of the prototype harness accessory, using an instrumented manikin, to assess the forces on the torso during fall arrest. The results of such research may encourage standards organizations and harness manufacturers to improve regulations and harness designs to reduce the potential for suspension trauma.

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