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Suspension Trauma and Fall-Arrest Harness Design

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CONTENTS

ABSTRACT After a successfully arrested fall, fall victims may develop suspension trauma, a potentially fatal reduction of return blood flow from legs to the heart and brain, if they are not rescued quickly or the harness does not fit them well. This chapter describes human suspension tolerance time while wearing full-body harnesses, the factors that affect suspension tolerance, current suspension injury control measures, and rescue procedures.

KEY WORDS: *body weight, body shape, harness fit, suspension, anthropometry, fall arrest, rescue.*

8.1 Introduction

In 1995, the Occupational Safety and Health Administration (OSHA) mandated a construction standard that specified that full-body harnesses replace waist belts for fall arrest in a personal fall-arrest system, effective in 1998 (U.S. Department of Labor, 2011a). The

requirement has resulted in an increase in the use of full-body harnesses for fall protection. Along with the OSHA mandate, safety professionals and scientists have furthered our knowledge about fall protection over the past decades, including the fall-arrest harness fit assessment, post-fall suspension control, and post-fall rescue issues.

Once a worker's fall has been successfully arrested by a full-body harness, the suspended worker needs to be rescued promptly. A prolonged suspension can cause the pooling of blood in the legs and the reduction of the return blood flow to the heart. The motionless posture after a traumatic shock and restrictions of the femoral arteries and veins caused by the harness straps can worsen venous pooling. Other factors such as heat, dehydration, immobilization due to injury, neurological disorders, aging, or norepinephrine-transporter deficiency can further speed the detrimental effects, which may damage vital organs such as the kidneys (Seddon, 2002; Robertson, 2008; Shannon et al., 2000). This phenomenon of venous pooling is known as suspension trauma.

This chapter describes human suspension tolerance time while wearing full-body harnesses, the factors that affect suspension tolerance, current suspension trauma prevention practice, and rescue procedures. Suspension tolerance was defined by Streeten (1987) as the duration of motionless suspended time until any sign of medical orthostatic intolerance (a temporary loss of consciousness). The signs of orthostatic intolerance included (1) a systolic blood pressure (BP) decrease of more than 20 mm Hg below the pretest value; (2) a diastolic BP decrease of more than 10 mm Hg below the pretest value; (3) a heart rate (HR) increase of more than 28 bpm over the pretest value; (4) a HR decrease of more than 10 bpm from baseline; (5) a pulse pressure decrease to less than 18 mm Hg; or (6) an observed shortness of breath, nausea, dizziness, or diastolic BP greater than 100 mm Hg (Streeten, 1987).

8.2 Suspension Tolerance Time

Some laboratory studies have investigated the tolerance of participants to motionless suspension, mainly for men while wearing fall-arrest harnesses (Brinkley, 1988; Weber and Michels-Brendel, 1990). With small sample sizes, suspension tolerance, as measured, ranged from 3.5 to 60 min. Specifically, the literature has shown some variant results regarding tolerance time for the use of similar full-body harnesses: from 8 to 45 min ($N=5$) (Noel et al., 1978), 6 to 37 min ($N=2$) (Bariod and Théry, 1997), and 5.1 to 30.1 min (mean = 14.38, $N=13$) (Brinkley, 1988). The literature has also reported differences in suspension tolerance time for different styles of full-body harness, with an average of 17.1 min (minimum to maximum of 3.5–32) to 28.4 min (minimum to maximum of 10.2– 49.8) for four harness types ($N=10$) (Brinkley, 1988), as well as median suspension durations of 20–27 min for five styles of harness ($N=15$) (Weber and Michels-Brendel, 1990). In any case, suspension tolerance varies considerably from person to person. Scientists have speculated about the harness fit effect on suspension tolerance time because about half the trials in the mentioned studies terminated voluntarily by the participants, possibly due to discomfort caused by poor harness design or fit (Noel et al., 1978). In a recent controlled laboratory study, Hsiao et al. (2012) reported that the suspension tolerance time was measured to be an average of 29.1 min and that the harness fit to the human body played a role. The study also evidenced large variability ($s=12.1$ min, $N=37$) with a minimum to maximum of 5–56 min (Figure 8.1). With a comparatively larger sample size ($N=37$), the study provided
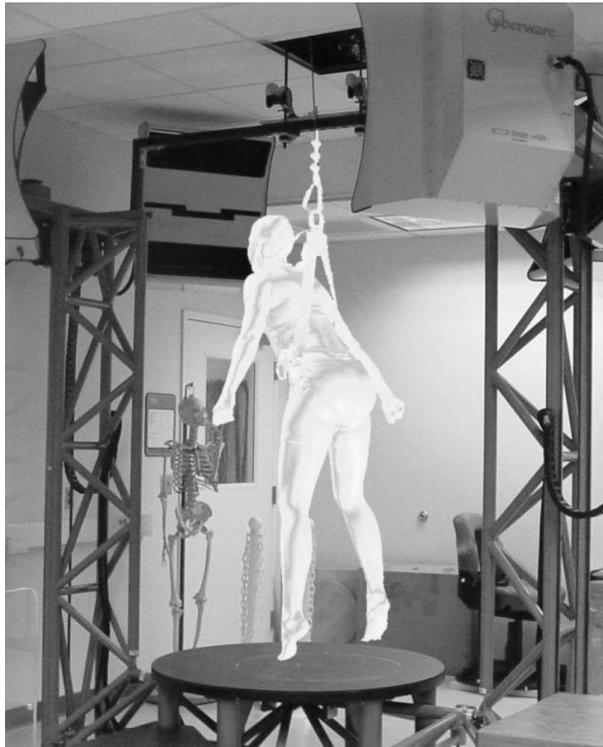
FIGURE 8.1
A custom-made suspension system was used to suspend the participant for a suspension-tolerance capability test and for registering the interface between the harness and participant.

the most updated data for estimating the time constraints in rescuing a worker suspended after a fall. It is worth noting that the range of the participants' body weight in this study was 50–107.6 kg, although the harnesses have been designed to accommodate 50–141 kg. Given that body weight has a negative correlation with suspension tolerance time, harness users with a body weight above 107.6 kg may experience an even shorter suspension tolerance time than that reported in this study.

8.3 Factors That Affect Full-Body Harness Suspension Tolerance

8.3.1 Body Weight and Stature Effects

Researchers have reported that body weight (Turner et al., 2008) and stature (Seddon, 2002) were predictors for suspension tolerance. Specifically, the Pearson correlation coefficient showed significant negative correlations between suspension tolerance time and body weight ($r = -.45$, $p = .005$) and stature ($r = -.43$, $p = .007$) (Hsiao et al., 2012). In practical harness–torso interface design applications, greater upper-torso depth ($r = -.37$, $p = .02$) and lower-torso depth ($r = -.36$, $p = .03$) are associated with shorter suspension tolerance time

(Hsiao et al., 2012), which is understandable since greater upper- and lower-torso depths generally correspond to heavier body weights.

8.3.2 Gender Effect

An absence of gender difference in the ability to tolerate harness suspension has been reported elsewhere (Weber and Michels-Brendel, 1990). However, the true effect cannot be determined in that there were only three and four women in the two tests of the Weber and Michels-Brendel study. In a recent study, a mean suspension tolerance time comparison by gender also revealed no significant difference ($p = .261$). The mean suspension tolerance time was 27.1 min for men (95% CI: 21.2–33.0; $N = 20$) and 31.6 min for women (95% CI: 25.7–37.6; $N = 17$) (Hsiao et al., 2012). While the larger sample size (17 women) in that study offered a good prospect for examining the gender effect, an obstacle remained. The study was not a matched-pairs study; 71% of the female participants weighed less than 70 kg, while 80% of the male participants weighed above 70 kg. With the confounding between gender and body weight, the insignificant effect of gender (anatomical and physiological characteristics) ($p = .26$) cannot be confidently confirmed.

8.3.3 Effect of Harness Fit to Human Body

Harness fit can be attributed to four key parameters: harness ring location (static fit to body), torso angle of suspension, strap configuration, and human body characteristics (i.e., size and shape) (Hsiao et al., 2009a).

8.3.3.1 Static Fit (Harness Ring Location)

There is a general understanding that the harness dorsal D-ring should be positioned between the inferior and superior borders of the scapula while the harness user is standing. Also, the chest ring is to be placed at the sternum area. Harness manufacturers have more detailed ring-location specifications, which are generally included in product manuals. In the past, fall-arrest harnesses were designed based on the body dimensions of male workers; static harness fit was in general worse for women than for men (Hsiao et al., 2003). However, harness users need to be aware that a static fit does not guarantee that a person suspended motionless in such a harness will be exempt from suspension trauma (Hsiao et al., 2012).

8.3.3.2 Torso Angle of Suspension and Suspension Fit

The second element of harness fit to the user's body is the torso angle of suspension (Hsiao et al., 2009a). The angle of suspension is measured between the torso center line and the harness vertical suspension line (Figure 8.2a). Using a rigid torso dummy for drop testing, the American National Standards Institute (ANSI) Z359.1 standard specifies that the suspension angle at rest shall not exceed 30° (ASSE, 2015). The Canadian CAN/CSA-Z259.10-06 standard also allows a maximum angle of 30° (CSA, 2006). The International Organization of Standards (ISO) 10333-1 and European EN 361standards allow maximum angles of 45° and 50°, respectively (ISO, 2002; CEN, 1992). These standards, however, do not elaborate on why these angle limits were specified and how they affect suspension tolerance (Seddon, 2002). A recent study showed that participants with a suspension angle >35° had shorter suspension tolerance time than those with smaller suspension angles ($p < .001$). Respective
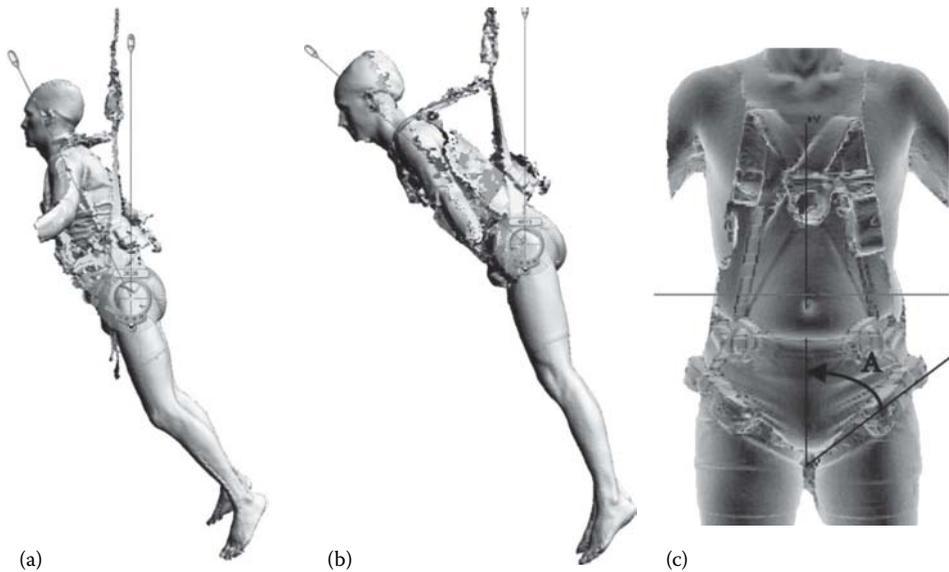
(a)   (b)   (c)

FIGURE 8.2
The angle of suspension is measured between the torso center line and the harness vertical suspension line.
(a) The suspension fit rating is a pass (angle of suspension = 26°); (b) the suspension fit rating is a fail (angle of suspension = 48°). The thigh-strap angle A in (c) is defined by the line that connects the highest point and the lowest point of the thigh strap and in reference to the body sagittal plan.

suspension times were 34.9 min (95% CI: 30.1–39.6; $N = 22$) for the group with the smaller angle of suspension (angle of suspension $\leq 35°$) and 20.9 min (95% CI: 15.9–25.8; $N = 15$) for the group with the greater angle of suspension (angle of suspension $> 35°$) (Hsiao et al., 2012; Figure 8.2b).

In a critical review, Seddon (2002) was puzzled as to why the maximum angle requirements were set differently in different standards. From the perspective of biomechanics, an increased torso suspension angle results in a larger moment arm at the low back, which, in turn, can cause lower-back discomfort and increased consumption of oxygen, thus posing an increased risk of suspension trauma. When the torso suspension angle is more than 30°, the force imposed by the weight of the upper body will increase dramatically, based on the basic trigonometric concept. The harness industry and fall protection professional community can consider testing body-harness designs using a series of anthropometric manikins in suspension and checking on suspension angles, in lieu of relying on traditional static-fit testing criteria to provide an increased protection against suspension trauma.

8.3.3.3 Thigh-Strap Angle

The third element for harness fit is thigh-strap configuration fit (thigh-strap angle). The thigh-strap angle is defined as the angle between the thigh strap and the sagittal plane (Figure 8.2c). A study of 216 participants using an overhead-style harness revealed that a greater thigh-strap angle from the sagittal plan was correlated with an increase in torso suspension angle and hence in harness-fit failure (Hsiao et al., 2007). The thigh-strap angle may be considered as a fit criterion to possibly minimize the need for a suspension test to predict the angle of suspension and suspension tolerance.

8.3.3.4 Body Size and Shape and Effect of Harness Match Level

The last element for harness fit is human body size and shape. Past studies have shown that body weight is a fair predictor for suspension tolerance (Turner et al., 2008; Seddon, 2002) and that a relatively bulky chest combined with a short torso is associated with a poor harness-fit rating (Hsiao et al., 2009b). A previous study has also shown that individuals who used a size of harness that was different from the best-fit size had shorter suspension tolerance times (Hsiao et al., 2012). Individuals with disparity of body dimensions often are "forced" to choose a harness size that does not fit their body, thereby increasing their risk of suspension trauma.

Large changes have taken place over the last decades in body dimensions among the U.S. civilian population (U.S. Department of Health and Human Services, 2001), and the harness industry has updated harness sizing systems based on government research suggestions (Hsiao et al., 2009a,b). Workers whose combination of body weight and stature is at the proximity of the size boundaries of the sizing scheme continue to need to try on more than one size to select the best-fit size because the overall combination of their body dimensions (i.e., body shape) governs the size; some of their body dimensions may fall on different sides of the boundaries. When purchasing a safety harness, clearly, the harness should be tested so that an individual can find a model that best fits the shape of his or her body, thus delaying the onset of suspension trauma (Bariod and Théry, 1997).

8.4 Current Prevention and Protection Practice

8.4.1 Rescue Time

Past studies have reported a wide range of suspension tolerance times among individuals, from 3.5 to 60 min. With small sample sizes, typically 2–13 participants, most studies in the literature did not or were unable to suggest a required critical time frame in which to rescue a victim. Hsiao et al. (2012) suggested that a rescue action be accomplished in 9 min. This was proposed based on the fact that the mean and standard deviation of suspension tolerance time were 29.2 and 12.1 min, respectively, from 37 participants and that the data are normally distributed: $T_{0.05} = \text{mean} - (1.645 * s) = 29.2 - 1.645 * 12.1 = 9.26$ min. This is to ensure that no more than 5% of suspended workers would experience suspension trauma. The explanatory information in ANSI Z359.2 recommends a goal of establishing contact with the fall victim within 6 min after a fall incident (Feldstein, 2007).

8.5 Rescue Procedure

Under 29 CFR 1926.502 (d) (Fall Protection Systems Criteria and Practices), OSHA requires that employers provide for "prompt rescue of employees in the event of a fall or shall assure that employees are able to rescue themselves" (U.S. Department of Labor, 2011b). To fulfill this requirement, three topics must be understood: signs and symptoms of suspension trauma, suspension trauma control, and post-rescue treatment.

8.5.1 Signs and Symptoms of Suspension Trauma

Workers should be trained to be aware of factors that can increase the risk of suspension trauma and the symptoms of trauma. In general, body characteristics (i.e., weight, stature, upper- and lower-torso depths), and poor harness fit are associated with decreased suspension tolerance time. The signs of developing suspension trauma include a systolic BP decrease of more than 20 mm Hg below the individual's normal value, a diastolic BP decrease of more than 10 mm Hg, a HR increase of more than 28 bpm, a HR decrease of more than 10 bpm, a pulse pressure decrease to less than 18 mm Hg, shortness of breath, nausea, dizziness, and a diastolic BP greater than 100 mm Hg (Streeten, 1987).

8.5.2 Suspension Trauma Control

To reduce suspension trauma risk, workers are to be trained to use fall-arrest systems correctly while performing their jobs. They also need to know that they can move their legs during a suspension to reduce the risk of venous pooling. Many fall-arrest harnesses have a pair of "built-in" footholds. Harness users need to be familiar with the use of footholds to alleviate pressure and delay symptoms. In addition, efforts should be made to rescue suspended workers as quickly as possible. Moreover, everybody who is suspended in a safety harness runs the risk of shock and unconsciousness due to trauma incident consequence; a prototype self-deployable suspension trauma-relief accessory that converts a suspension posture to a seated posture at the moment of a fall was proposed, which can significantly delay the onset of suspension trauma (Turner et al., 2008).

8.5.3 Post-Rescue Treatment

The best method to recover harness suspension victims has not been clear over the past 20 years, with some authors advising against standard first-aid practices (i.e., placing victims in a horizontal position), while others have contended that there is no evidence to support the safety or efficacy of positioning a victim in a semi-seated position. Some safety training materials published in the early 2000s have emphasized that the victim should be positioned with the upper body raised, that is, in a seated or possibly squatting or crouched posture. The rationale was that laying the victim down horizontally can be life threatening because blood that has accumulated in the legs can flow abruptly into the heart, creating a risk of heart failure due to overstrain. The concept can be traced back to a harness suspension information report (Seddon, 2002) that cited a German report on first aid following suspension in a fall-arrest harness (Lieblich and Rensing, 1997). This positioning recommendation was also supported by an earlier conference proceeding paper, which contended that rescued suspension victims may experience adverse effects if laid horizontally (Flora et al., 1972).

Through a systematic review of 29 papers relevant to the subject, Adisesh et al. (2011) identified nine articles as a basis for guideline recommendations and concluded that no evidence indicates the efficacy or safety of positioning a victim in a semiseated position. They suggested that the standard first-aid guidance for recovery of a semiconscious or unconscious person in a horizontal position be followed. OSHA has updated its suspension trauma/orthostatic intolerance information bulletin (U.S. Department of Labor, 2011b) by removing the statement that "Some authorities recommend that the patient be transported with the upper body raised" from the earlier version (U.S. Department of Labor, 2004). Other first-aid practices include unfastening all restrictive belts and clothing, calling a doctor, and continuously monitoring respiration and circulation as necessary.

8.6 Summary

Body weight, stature, and upper- and lower-torso depths were negatively correlated with suspension tolerance time. Harness suspension angle, thigh-strap angle, and harness-size match level were also precursors for suspension tolerance. Selecting well-fitting harnesses and establishing a 9-min rescue plan are suggested to ensure that no more than 5% of suspended workers would experience suspension trauma. This short rescue time is challenging. A self-deployable suspension trauma relief accessory or mechanism that can be integrated into harness design to further harness-user protection would be useful. To avoid any post-rescue injuries, the current practice is that the victim be positioned in a horizontal posture, per the standard guidelines for the recovery of an unconscious or semiconscious person after a rescue.

8.7 Disclaimer

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

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