Usability of Fall Arrest Harnesses

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ABSTRACT

Falls are a major contributor to construction-related fatalities. Many construction fall fatalities occur during roofing, and may be prevented by proper use of fall protection. A prevalent option for fall protection is a personal fall arrest system (PFAS). However, full adaption of PFAS is hindered by usability issues, particularly in the harness component. Current research aims to develop design requirements for more usable fall arrest harness. A study was conducted to consider the inter-relations of objective measures of fit and strap pressure, along with subjective usability measures including discomfort ratings and post-task questionnaire responses.

18 local roofers were recruited to test three different harnesses, while performing both quiet calibration-oriented trials and simulated roofing tasks. Significant correlations between discomfort ratings and pressure values were found only in quiet trials. Questionnaire responses were validated by inter-correlations and by significant correlations with discomfort ratings. Multiple comparisons of objective fit values and questionnaire responses revealed deficits in the low-end harness, while suggesting few differences between the mid- and high-range harnesses.

Results from analysis of both objective and subjective measures were considered alongside free-response prompts to develop a set of four requirements for consideration in future harness design, including a lowered harness weight, an intermediate level of padding, inclusion of rolling style vertical strap quick-adjusters, a belt-style thigh strap adjustment mechanism, and the adoption of a three-sized sizing scheme.

Statement of Originality

I hereby certify that all of the work described within this thesis is the original work of the author. Any published (or unpublished) ideas and/or techniques from the work of others are fully acknowledged in accordance with the standard referencing practices.

Joseph Angles

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1. Introduction

1.1 Prevalence of Falls and Fall Arrest Systems

Falls are a major safety hazard in the construction industry, accounting for 34.6% of all fatalities among construction workers in 2010 (BLS, 2010). Of these falls, 33.8% occur during roofing work. Many of these incidents occur on residential construction sites, where fall heights are relatively low (usually 30 feet or less) and the use of personal protective technologies (PPT) related to fall protection is not common. Lipscomb et al. (2008) remarked that within residential construction, falls are the leading cause of workplace fatalities.

Resulting from the prolific occurrence of falls in residential construction, OSHA directive 1926.501(b)(13) was enacted on September 16, 2011 requiring residential construction employers to implement the use of fall protection on all work above a height of six feet (OSHA, 2010). Under the guideline, OSHA delineates three acceptable forms of fall protection for construction of residential roofs: safety nets, bracket scaffolds, and fall arrest systems. Safety nets must span the entire area under the range of motion for all workers above 6 ft. Bracket scaffolds are temporary installations of guardrails that span the bottom perimeter of a roof. Anchors refer to the anchorage to which a lifeline is attached. Though fall arrest anchorage may be found in many forms, most are typically temporary installations of small brackets. Due to the time, technical proficiency, material burdens, and costs involved in the assembly of netting or guard rail systems, the most efficient fall protection method available for residential construction is a fall arrest system composed of an anchor, lifeline and safety harness.

OSHA 1926.502 Fall Protection Systems criteria and Practices (2010) does not address usability or ease-of-use in selection and/or design of FAS, in spite of well-supported guidelines related to usability that are applicable to PPT (e.g., ISO/TR 16982:2002). Residential construction is typically an informally learned trade, limited by constraints in time and resources (Angles, 2012). Thus introduction of PPT may be met with barriers to adaption, as education and resources to acquire a new technology may be limited. A recent study by Smith-Jackson et al. (2011) identified several usability problems based on roofers' self-reports. The most frequently reported factors in roofers' negative opinions of fall arrest systems included difficulty in movement, discomfort, and entanglement with the system's lifeline. Additionally, roofers reported an association between fall arrest harness usability and risks of falls. Roofers, for instance, believed that fall arrest harnesses could increase the risk of falls via entanglement, discomfort, and distraction (Smith-Jackson et al., 2011).

The use of fall arrest systems faces resistance due to such problems as lack of usability, as well as thigh and shoulder discomfort associated with fall arrest harness usage (Angles et al., 2012a). Current research efforts are focused on the development of adequate anchorage systems, but the interface of these systems with end users has been sparsely explored. Providing guidelines for incorporating comfort and usability in fall arrest systems may increase willingness to comply with OSHA regulations for residential construction, lending toward a reduction in workplace fatalities. To improve usability of fall arrest harnesses, a systematic method of measuring physical attributes of harness wear and user perceptions is needed. This project proposes a method to discover associations of harness strap pressure with user perceptions of discomfort.

1.2 *Prior Study of* Physic*al Properties in* Wearable *Straps*

Existing research on backpacks may be generalizable to fall arrest harnesses. Martin et al. (2000) examined the effects of strap design on discomfort and pressure distribution associated with backpack use. A map of shoulder zones established a method to define areas prone to shoulder discomfort associated with each type of strap. A load carriage simulator used rigid backpack-equipped mannequins atop a pneumatically driven platform to simulate anterior/posterior and medial/lateral leans (Mackie et al., 2005). A proprietary configuration of load cells in combination with a Tekscan™ pressure sensor was used to provide quantitative comparisons between different load carriage configurations. Bryant et al. (2001) validated the use of this measurement system to predict user discomfort, establishing a correlation coefficient of $r = 0.66$ between shoulder pressure and reported discomfort.

The established study of relationships between mechanical measurements and discomfort ratings to backpacks presents an opportunity to transfer similar methodology to fall arrest harnesses. To date, little research has been conducted related to discomfort measures or usability of fall arrest harnesses. The use of fall arrest harnesses presents physical stresses that are comparable with characteristics studied in backpack usage, as there is tension of individual adjustments about the user's shoulders and waist. As such, similar methods and instrumentation configurations may be applicable to study the effects of harness pressure, aside from natural differences in load magnitude and direction associated with context of use. Furthermore, an additional source of discomfort when using fall arrest harnesses occurs in the thigh area (Smith-Jackson et al., 2011, Angles et al., 2012a). As backpack studies have primarily explored waist-up forces (Mackie et al., 2005; Bryant et al., 2001), additional considerations must be made in order to objectively measure a full harness system.

1.3 *Factors Influencing Harness Discomfort*

Waist-belt harnesses were commonly used as a last line of protection against falls until the 1950s, when full-body harnesses were determined to be biomechanically superior due to reduced risk of trauma to the torso region (Brinkley, 1988). At the time of inception, full-body fall arrest harnesses were designed under anthropometric guidelines of the same military data used to design parachute harnesses (Bradtmiller et al., 2000). Although more recent military-generated anthropometric data are available, it is not necessarily representative of construction workers. Military-generated data may be biased toward particular physical representations due to stringent physical requirements for entry into service.

Additional anthropometric data from entities such as NASA and ISO (ISO, 2010, NASA, 1978) may not represent the construction working population as well, and may not accurately represent fit statistics for harness design to the extent that three-dimensional (3D) imaging can achieve. A study performed in 2003 examined existing fit schemes of harnesses manufactured to current ISO and OSHA standards and regulations (Hsiao et al., 2003). Seventy six males and 32 females were divided between two harness types: overhead and vest-type (Figure 1.1). Harness size for each trial was selected according to the manufacturer's printed sizing recommendations.

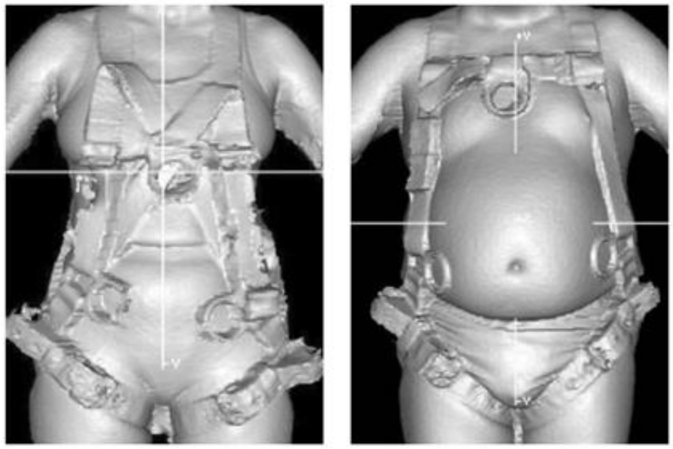

Figure 1.1: Vest-Style and Overhead-Style Harnesses (Hsiao, 2007)

Participants wore the harness while standing and while suspended, and were tested via 3D imaging for ten test-fit parameters. Of the parameters, six were subjective criteria based on participant self-report or researcher observation. The four measured criteria included location of the back D-ring (should be between participant's shoulder blades for proper force distribution), tightness of thigh straps (should be able to snugly fit two fingers between thigh and strap), hip ring location (anterior to body center of gravity), and torso angle during suspension (harness should hold body a maximum of 30° from vertical in suspension). The quality of "fit" could pass or fail in either the standing or suspended position, or both. 47% of males and 30% of females failed the fit test for overhead harnesses. In comparison, 29% of males and 50% of females failed the fit test for vest-type harnesses. In total, over 39% of participants failed Hsiao's fit tests when following manufacturer's guidelines. During trials, Hsiao collected 3D body scans to be used toward formulating revised fit guidelines.

Subsequently, Hsiao (2007) conducted a study of harness fitting that reduced a logistic regression model to a simplistic fitting scheme based on a participant's height and weight.

Participants included 108 males and 108 females, age 18 – 56. Samples included White, Black, Hispanic, and Other (mixed race) participants; 27 of each race participated per gender group. Again, both overhead and vest-type harnesses were considered. In order to fit, the human-harness interface had to meet four criteria (Figure 1.2) The back D-ring of the harness had to be positioned between the inferior and superior scapula borders (Figure 1.2a). When the participant was suspended, the suspension angle had to be 35° or less (Figure 1.2b). The chest strap could not make contact with the neck (Figure 1.2c), and the hip rings had to pass over the participant's center of gravity (Figure 1.2d).

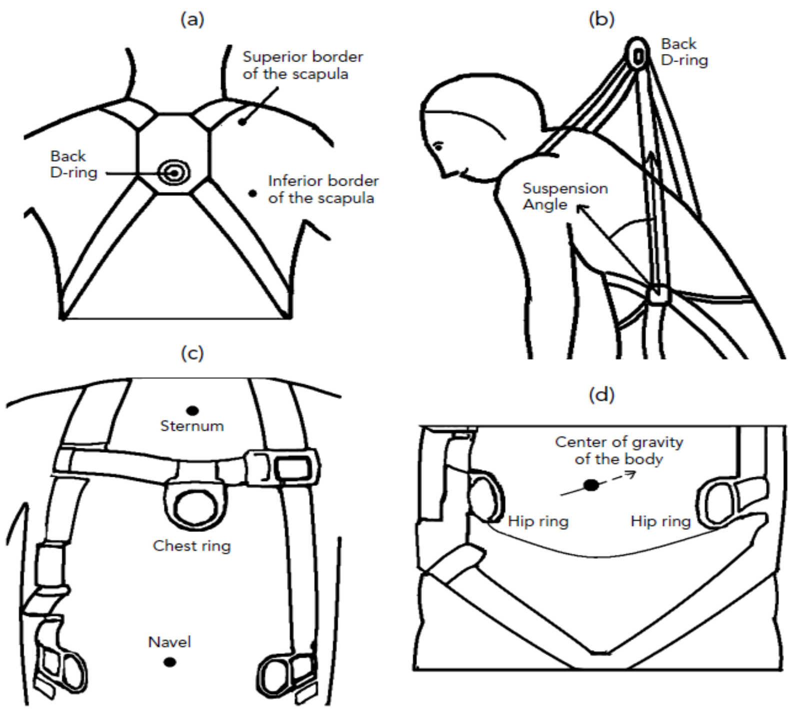

Figure 1.2: Fit Criteria for Fall Arrest Harnesses (Hsiao, 2007)

Using predictors of stature, weight, and both upper and lower torso breadth and depth, Hsiao (2007) developed a logistic regression model to successfully classify 99% of the classification subset of participants into one of four overhead harness sizes (extra small, standard, extra-large, or super extra-large). Logistic regressions were reduced to a more accessible model using only weight, height, and gender as size predictors (Figure 1.3). The reduced model successfully classified 94% of both genders' validation sets. Of particular note, the "super extra-large" designation does not appear in the resulting model, as apparently no participants exceeded the dimensions of appropriate fit for an XL-sized harness.

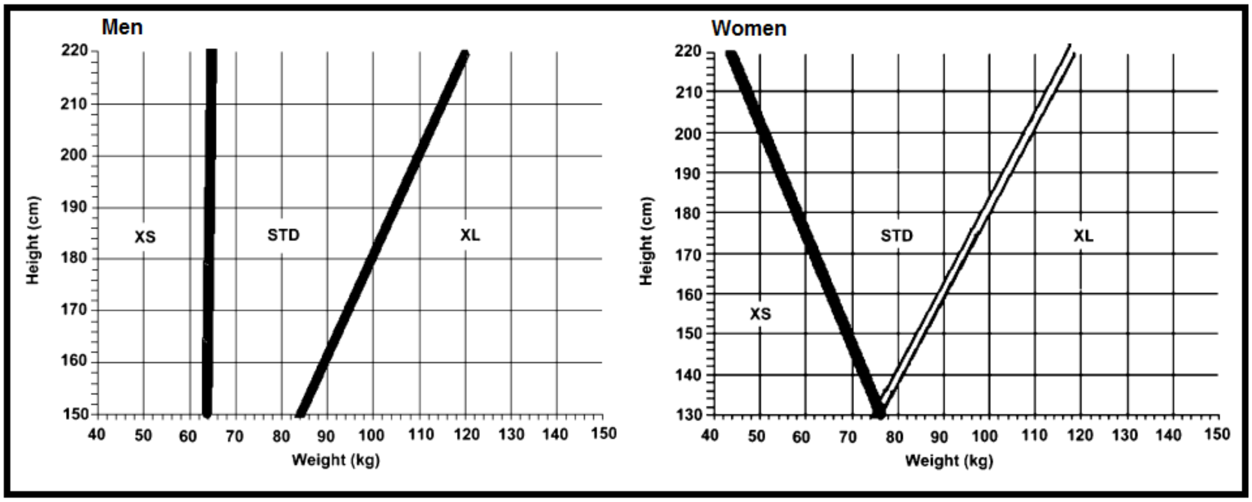

Figure 1.3: Sizing Scheme of Overhead Harnesses by Gender (Hsiao, 2007)

Sizing structures were subsequently further validated and proposed for implementation in design (Hsiao et al., 2009). Mine Safety Appliances (MSA) (2010) has adapted Hsiao's harness fit recommendations in the sizing scheme for the EVOTECH™ fall protection harness line. Figure 1.4 shows the sizing scheme for sizes Small – X-Large. Note that the Super Extra Large designation was removed, as participants qualifying for this size would be excluded from studies within the scope of this project. Additionally, DBI-SALA has signed a letter of agreement to conform to Hsiao's sizing scheme. As of August 2012, DBI-SALA and MSA are the only two manufacturers under such an agreement.

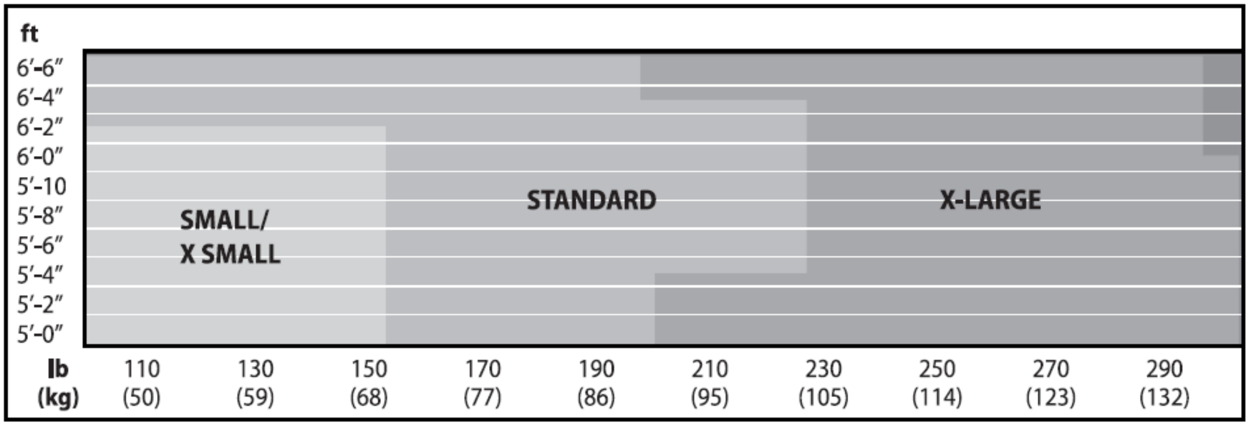

Figure 1.4: MSA EVOTECH™ Fall Arrest Harness Sizing Scheme (MSA, 2010)

1.4 *Ensuring Ecological Validity: The Case for a Scaled World*

The need for ecological validity in usability testing imposes concerns when replicating a real world scenario within a laboratory setting. According to Brewer (2000), ecological validity requires that the materials, methods, and setting of a study must approximate the intended real life scenario. As the methods and materials used in real world residential roofing construction can be simply replicated in a simulated environment, setting is the primary concern when considering ecological validity in the context of reducing construction tasks to a laboratory environment.

The concept of emphasizing ecological validity originated in psychology, but has diffused to other applications involving human participants. Bronfenbrenner (1977) describes the layers of an ecological system that have an effect on participants, including the microsystem-level relationships that participants rely on to perceive realism. Subsequently, Bronfenbrenner proposes a definition of ecological validity as the extents to which participants perceive that a laboratory environment contains the properties that the experimenter intended. Bronfenbrenner further acknowledges the macrosystem, or the overarching structure of culture under which participants form context, as an essential consideration in research design to ensure results are ecologically valid.

Researchers have generally identified the components of ecological validity as environmental setting, stimulus realism, and task type (Brunswick, 1943; LeBlanc et al., 2011; Neisser, 1976; Rivera, 1999). The quality of the environmental setting pertains to the extent to which the physical surroundings of a study approximate the natural environment of the task's occurrence in a real-world setting. Naturalistic or quasi-naturalistic settings provide context to facilitate natural behaviors and thought patterns, thus reducing effects of modified performance due to the laboratory setting. Stimulus realism refers to activity units within the laboratory environment. Minimalist approaches may reduce activities under the assumption that reduced stimuli are advantageous to validity, providing a smaller margin of error. However, reduced stimuli may neglect ecological validity by losing realistic contexts associated with non-reduced tasks. Sub-components of tasks may be reduced by necessity of environmental constraints, but the implications for performance formed by complex interrelationships of stimuli must remain true to form to ensure ecological validity. Under this model of ecological validity, the final dimension of consideration is the task type or behavior to be studied. Consistent with the concept of stimulus realism, experimentally studied tasks should be similar to real world tasks. Thus, the experimental tasks should elicit similar cognitive and behavioral responses to real world tasks.

A scaled world is a simulated experimental environment that maintains carefully considered functional relationships derived from a real world environment (Ehret, Gray and Kirschenbaum, 2000). Realism and complexity of the setting is maintained, while non-essential aspects of the real world setting may be excluded for experimental purposes. In developing a scaled world, an essential consideration is the determination of which functional relationships must be maintained during the scaled reduction of a real world task. The goal in this reduction is to maintain an environment under which research findings may be generalized to the original task, as opposed to finding results valid only for a specific task environment (Gray, 2002). Scaled worlds additionally provide an opportunity to strategically eliminate unpredictable variables in a controllable and replicable environment. The reduction of unpredictable variables during task performance emerges as a necessity when studying particular variables from a highly complex experimental environment, such as a roof under construction.

An additional advantage to scaled world environments is measurability of precision due to replicable experimental sessions. While field studies permit a one-time opportunity to record data, scaled worlds allow for repeated trials within a controlled environment (Elson, 2003). Such repetition allows for construction of methods to consistently code video and audio data, and return to the recordings for further review. Additionally, multiple trials may be implemented to ensure reliability of instrumentation. Finally, controlled environments can ultimately be less costly than implementing field studies, as fewer personnel may be required for experimental sessions, and participants may be individually recruited and compensated without considerations for multiple employees and managers on construction sites.

However, the scaled world approach to setting is not without disadvantage. Ehret et al. (1998) listed potential threats to validity, focusing on naturalism and realism. The true work environment may provide a degree of naturalism that cannot be reflected in a laboratory setting, leading to adverse effects to the manner in which participants perform tasks. In reducing tasks to a scope consistent with a scaled world setting, it is often unavoidable to lose elements of real world tasks. The retained elements of real world tasks should be carefully considered in terms of which components have the greatest effect on ecological validity. The original work system should ultimately provide the frame of reference in the scaled world reduction.

1.5 Ecological Momentary Assessment

Behavioral research is often concerned with analyzing typical real world behavior. However, behavior is rarely observed as it occurs in the real world (Shiffman et al., 2008). Particularly in ergonomics research, observations often rely on retrospective or summary self-report. Such observations may limit the ability to analyze dynamic responses that occur due to changes in stimuli or setting. This may lead to a misunderstanding of the context of self-report, inadvertently disregarding changes in the immediate environment which lead to dynamic sequences of perception. Stone (1994) proposes the use of Ecological Momentary Assessment (EMA) as a solution to the limitations set forth by static retrospective observations.

EMA methods allow participants to give repeated, real world, real-time reports during studies, across time and setting changes (Shiffman et al., 2008). EMA is a collection of research methods that may be applied to various types of research, but most use of EMA encompasses several key features (Stone et al., 2007). Data collection occurs in a real world, real-time environment. This factor of EMA lends to its advantage in terms of ecological validity, as participants remain in their natural environment. Assessments are made to investigate a participant's current state, hence use of the word “momentary.” Observations are made after discrete events or very small passages of time, so negative effects of time passage inherent to retrospective reports are minimized. The selection of the time block defining a moment is a strategy typically based on either the occurrence of phenomena of interest to the study, or by random sampling techniques. Finally, multiple assessments are completed over the duration of the study. Repetition of assessments lends to analyzing the manner in which responses and perceptions changed over time and dynamic situations.

Christensen et al. (2003) present methods of collecting data outside of laboratory settings known as “experience-sampling.” Though the study presented herein will occur in a quasi-naturalistic setting inside a laboratory, several underlying concepts of experience-sampling remain pertinent to collection of momentary data from realistic environments. Experience-sampling only captures observations that a participant is able to convey, and only phenomena of which the participant is consciously aware (Feldman Barrett and Barrett, 2001). Episodic and semantic representations may be related, but can be distinguished (Klein, 2001). In the context of EMA, the division of semantic and episodic memory implies that a participant might not retain, process, and contextualize a previous momentary report. The result is that each data point is considered as a discrete observation representative only of the participant’s perception at the moment of collection.

Despite scientific advantages of EMA methods, several challenges exist in its implementation (Smyth and Stone, 2003). The sampling scheme must be carefully planned to adequately document important changes over the course of the study. Questionnaire design must portray valid methods in capturing the metrics it seeks. Since timing of response is central to the method, participants require an extent of familiarization prior to data collection. Furthermore, participants must be properly motivated to adhere to the research protocol, as they may become reluctant under the distractions of the task at hand. Finally, the monitoring of participants and administration of EMA methods may become problematic to researchers, as the ongoing study forces distraction on both the researcher and participant and forces both parties to periodically divide attention.

The analysis of momentary data provides another obstacle in the course of research design (Smyth and Stone, 2003). Although the accumulation of time-dependent data is among the primary advantageous attributes of EMA methods, it presents a challenge in the analysis phase of the study. Data must be aggregated according to time, type of occurrence, participant, or any combination thereof according to the study design. Sophisticated statistical models must be used to account for the vast amount of variables that might occur between or within participants. Decisions in regards to the treatment of random variables provide additional complexity to EMA during statistical analysis. Prior work has demonstrated effective approaches for each of these nuances (Affleck et al., 1999; Bryk and Raudenbush, 1992; Feldman et al., 1999; VanLeeuwen, 1997; Steiger et al., 1999).

Affleck et al. (1999) discussed the advantages of uncovering within-person relationships, and ultimately remark that mixed model statistical programming is advantageous when studying multilevel processes, such as momentary data among multiple participants. Bryk and Raudenbush (1992) delineated one approach to multilevel modeling, estimating variances explained by differences between and within participants by variable. Mixed model functionality is built into the SAS statistical package, indicating that it would be an appropriate tool for use in such application of multilevel modeling.

Consideration must be given as to whether within-person relations are random or fixed in nature. "Blanket" methods may treat all within-person relations as random coefficients, generalized to a population of within-participant relationships (Feldman et al., 1999). Careful consideration must be given to the broad use of random coefficients, as literature tends to be wary of the potentially significant effects of minor parameter changes in estimation (VanLeeuwen, 1997). Steiger et al. (1999) proposed using an empirical method of conducting statistical tests for parameter variance to determine between random or fixed designations for each within-participant variable. Though this would seem to be the intuitive approach, such testing is often neglected as analysis becomes simpler when the effect of error is eliminated from the model and all effects are considered fixed. Using blanket fixed effects, however, may not adequately specify variable relationships.

In summary, falls are a leading cause of construction fatalities, and mitigation attempts are hindered by poor usability of some personal protective equipment. There exists a deficit of research regarding fall arrest harness usability. To gain a stronger understanding of fall arrest harness use within a laboratory setting, a scaled world may be implemented in conjunction with ecological momentary assessment techniques. This approach allows for a repeatable simulated work environment, providing a basis for technology assessment in a quasi-realistic environment.

1.6 Purpose Statement

The purpose of this project was to measure physical attributes, judgments, and perceptions of fall arrest harnesses, and to disseminate findings as recommendations for application in future harness design. Four research objectives provided a progression from analyzing existing harnesses to developing recommendations. First, a system must be developed to quantify physical characteristics of pressure in different types of fall arrest harnesses. Subsequently, relationships of self-reported EMA-based usability metrics with harness pressure profiles were analyzed. Third, analysis of differences within EMA reports, pressure profiles, and questionnaire responses among different harness types will lend data toward determining desirable harness features. Design requirements for improved harness comfort and fit were developed, based on features that emerged as significant contributors to discomfort.

2. Methods

2.1 Experimental Design

A repeated measures, crossover trial design assessed the effects of pressure upon perceived discomfort across three harness types during the performance of quiet trials, and three simulated roofing tasks. Participants completed all tasks while wearing each of three harnesses in a balanced and randomized order.

2.2 Participants

A study on the relation between backpack strap force and user perceived discomfort found a correlation coefficient 0.66 (Bryant et al, 2001). This corresponds with a large effect size according to Cohen (1992). A value of $r = 0.6$ was used as a more conservative figure for sample size estimations. A two-tailed a priori t-test power analysis with $r = 0.6$, $\alpha = 0.05$, and $1\text{-}\beta \geq 0.80$ yields n = 17 participants with actual power = 0.82. However, to allow for balanced treatment presentations, n = 18 participants were recruited, with forecasted power = 0.85.

Participants were 18 years of age or older, had a minimum of one year of experience using fall arrest harnesses in a construction setting, weighed less than 310 lbs., and had no history of musculoskeletal injuries or disorders within the past year. Although recruitment was open to all races and genders, all 18 participants were white males. Informed consent approved by the Virginia Tech Institutional Review Board was obtained prior to beginning the experiment.

2.3 Harness Instrumentation

A system of pressure measurement in textile straps was created for installation in the fall arrest harnesses. This was achieved through use of both conductive Shieldit® film and resistive Ex-Static® textile. Two resistive layers were arranged between three conductive layers to effectively create a resistor that varies depending on the force acting upon it (Figure 2.1).

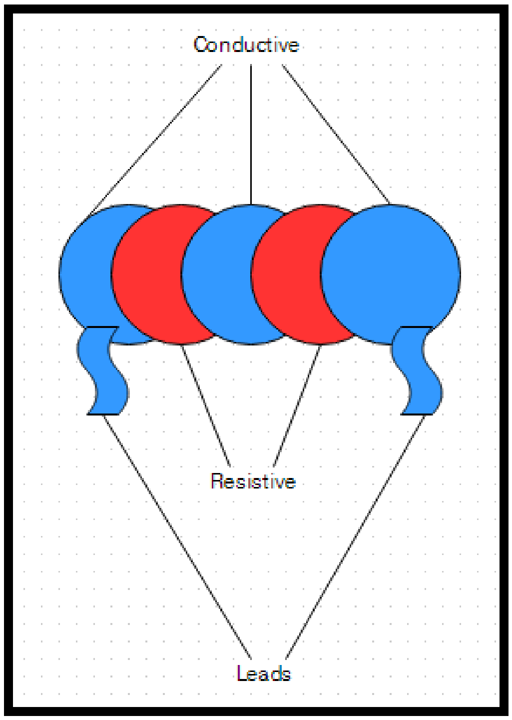

Figure 2.1: Diagram of Pressure Sensor Assembly

The process of creating sensors is illustrated in figures 2.2 – 2.7. Figure 2.2 shows all the textile and cardboard pieces used in creating sensors. Box 1 shows the center conductive piece, used to conduct current between the two resistive layers. Box 2 shows the resistive layer cutouts, two of which were placed in each sensor. Box 3 shows the conductive lead pieces. These leads were used to connect the sensors to Wheatstone bridges. Figure 2.3 shows the appearance of textile pieces fastened to cardboard backing, representing all the pieces used in one sensor. The cardboard-backed components were taped into place, represented in Figure 2.4. The completed sensor components were placed into a food-grade vacuum seal bag, as shown in Figure 2.5. The bag was selected for its ease in sealing, requiring only a vacuum source and a relatively low heat source; in this case, a household iron. Both of these tools are shown in Figure 2.6. Leads were cut through the bag, and the cuts were then resealed with plastic adhesive and a shrinkable plastic patch. The leads were then connected to a multimeter as the bag was vacuumed and sealed around one sensor at a time, and each sensor was compressed and sealed at 350Ω. Figure 2.7 shows a set of four completed sensors, which were stitched into a canvas cover as leads were attached to crimp-on connectors to withstand use while attached to fall arrest harnesses (Figure 2.8).

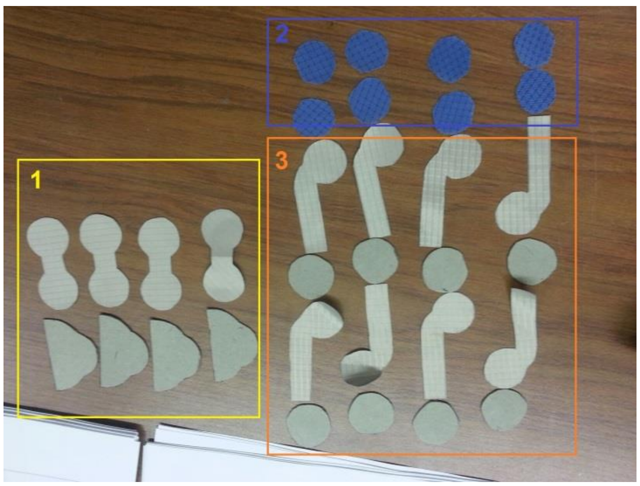

Figure 2.2: Textiles and Cardboard Cut-Outs

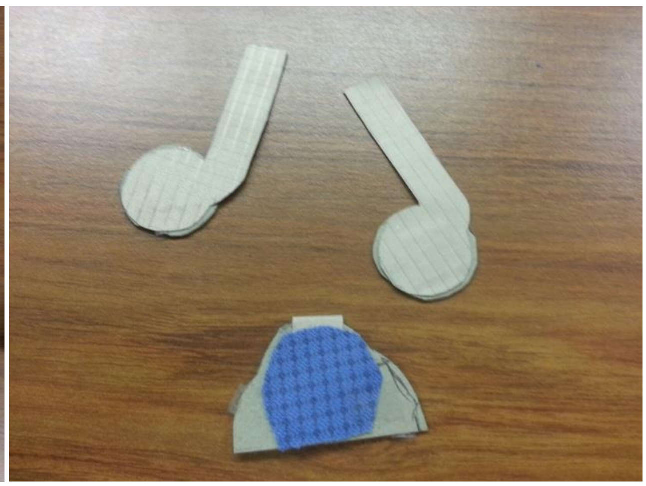

Figure 2.3: Textiles Fastened to Cardboard

Figure 2.4: Assembled Sensors Before Vacuum Seals

Figure 2.5: Sensors in Vacuum Seal Bag

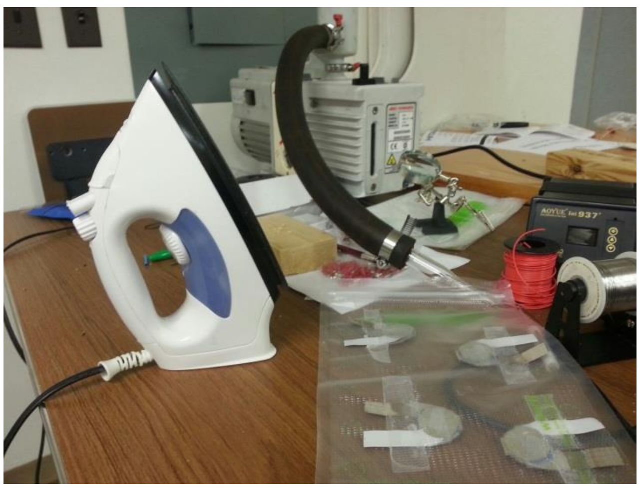

Figure 2.6: Vacuum Seal Bag, Vacuum Pump, and Iron

Figure 2.7: Sealed and Cut Out Sensors

Figure 2.8: Sensor in Canvas, Leads Wired for Harness Attachment

Deformation of the resistive layers by compression thins the material, which decreases the layers' electrical resistance by a small amount, ΔR. Pressure sensor circuitry were arranged in Wheatstone bridges, with one "active" arm. Wheatstone bridges are used to determine unknown resistance by measuring voltage output between four resistors, given a known input voltage (Figure 2.9, National Instruments).

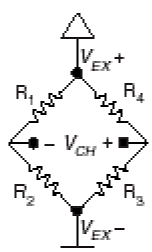

Figure 2.9: General Wheatstone Bridge Design (National Instruments)

Pressure sensors were vacuum sealed with a pre-loaded state of pressure, causing a stable resistance of 350Ω. Leads of each sensor were wired to three 350Ω completion resistors in order to complete a Wheatstone bridge in the quarter-bridge configuration. Figure 2.10 displays a representation of the completed circuit, in which R4 is the pressure sensor while R1, R2 and R3 are completion resistors. For the purposes of this project the lead resistances (R_L) were negligible and not considered in future calculations.

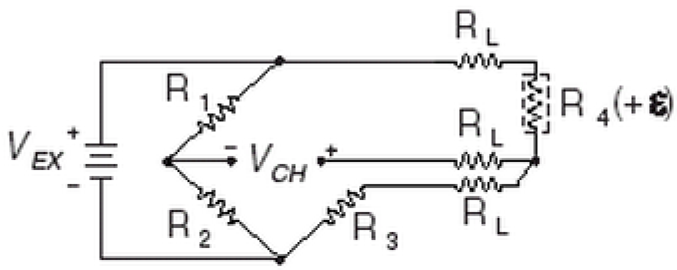

Figure 2.10: Wheatstone Quarter-Bridge Configuration (National Instruments)

To output signal from the pressure sensor, an excitation voltage (10V) was applied across the bridge (V_{EX}), and the diminished channel voltage (V_{CH}) due to dissipated excitation power was measured across opposing arms of the bridge. A National Instruments (NI) Data Acquisition (DAQ) card was interfaced through NI LabVIEW to collect the channel voltage from each Wheatstone bridge circuit. Thus a total of four Wheatstone bridge configurations in four separate signals were used for each harness.

All four sensors were connected to remotely located Wheatstone bridges via Ethernet cable. Only a single cable was required for each harness, as the eight sensor leads corresponded to the eight-pin Ethernet connection. Wires were stitched along the exterior of harness straps, and the Ethernet connection point was located on a strap crossing on the left thigh of each harness (Figure 2.11). This method of attachment allowed for relatively unobtrusive instrumentation, as the only part of the system making human contact was the canvas-covered sensor. To minimize its salience during task performance, the Ethernet cable was laid in the same direction as the pneumatic tools' air hose.

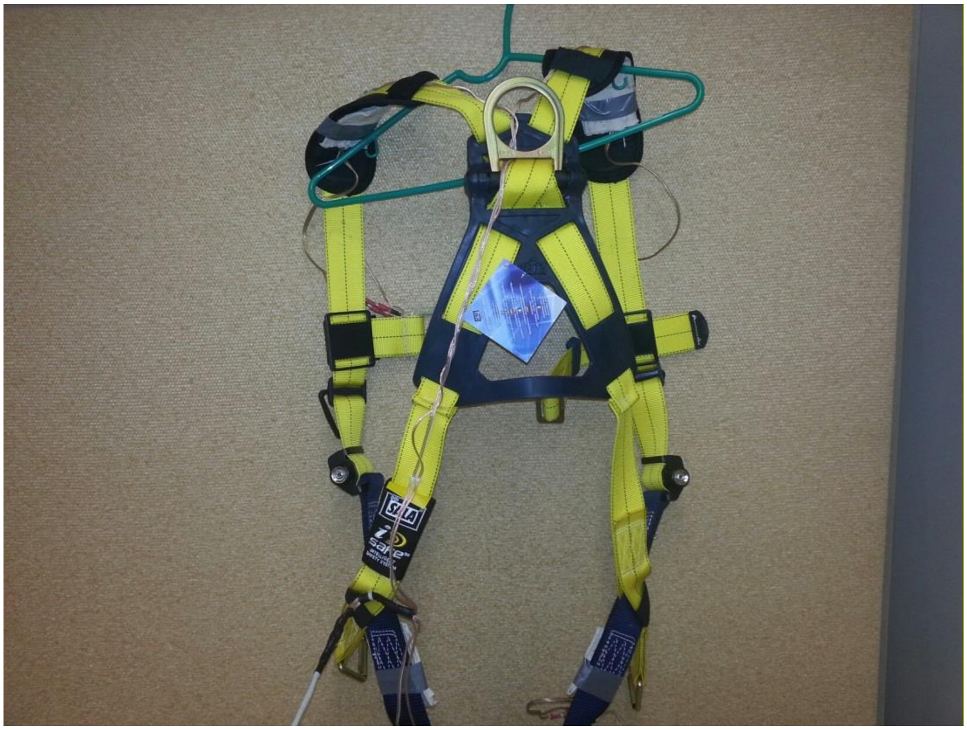

Figure 2.11: Fully Wired Harness

As the sensors were created from textiles, repetition in use caused small shifting of materials over time, leading to variances in output. To offset the effects of repeated use, each sensor was individually calibrated for pressure output prior to beginning of each participant's trials. Calibration was performed in LabVIEW, simultaneously recording output from a pre-calibrated load cell and each pressure sensor at 100 Hz. For each calibration, the load cell was pressed upon the pressure sensor and fully released, with at least three repetitions as permitted by a 5-second collection time. Example output from a calibration session can be seen in Figure 2.12.

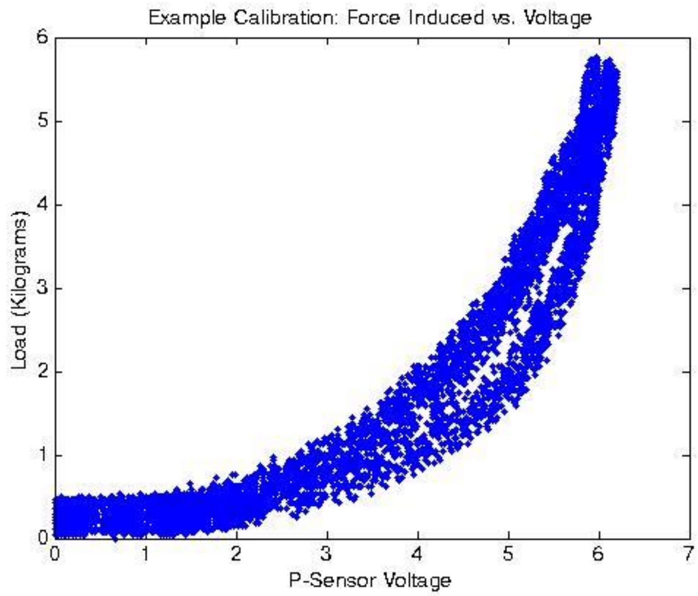

Figure 2.12: Sample Calibration Data Representation

Subsequently, MATLAB's curve fitting tool was used to model an exponential fit for each calibration session (Figure 2.13). The fitted line (represented in red) corresponds to the curve described by exponential parameters a and b, such that, for load in kilograms and voltage in volts, $\{load = a^{b * voltage}\}$.

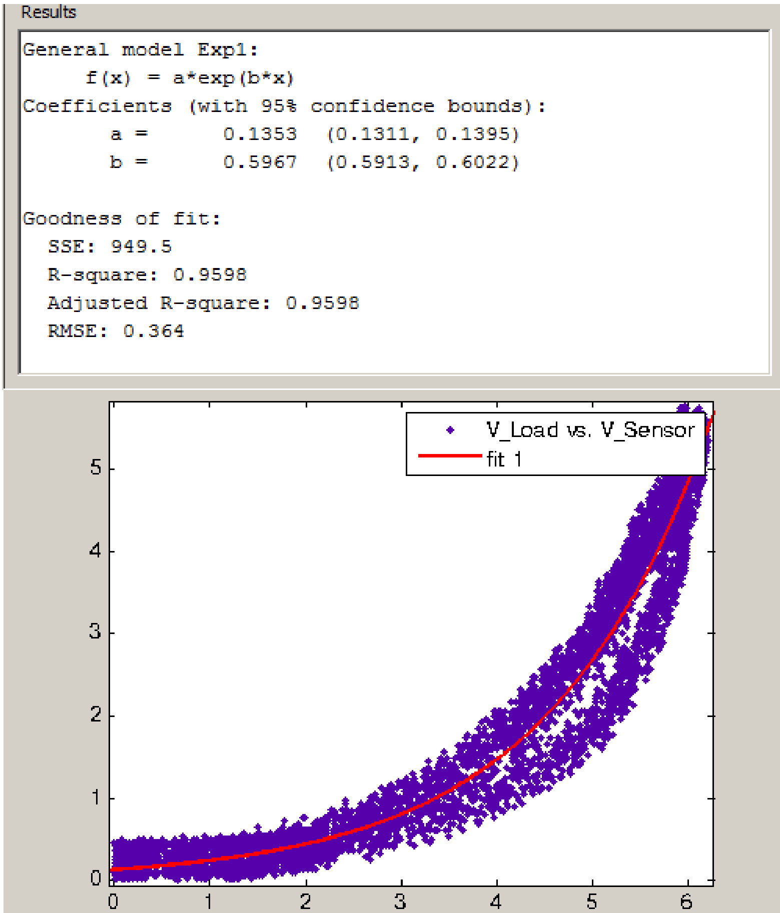

Figure 2.13: Example Curve Fitting of Force vs. Voltage

Thus a separate equation was derived for each sensor prior to each session. All data were processed through appropriate equations upon completion of collection. Note that data were calibrated to correspond with force (N) to conform to the calibration of the load cell. As the quantity of interest in this project was pressure, a conversion factor was applied to convert Newtons to pounds-force (1 N ≈ 0.2248 lb_F), and the quantity was divided over the area of the 1-inch diameter sensor (area ≈ 0.7854 in^2) to effectively convert the unit of measurement to pounds per square inch (psi).

2.4 Lab-based Fall Arrest System

Participants were subjected to three different harness types: (1) a “low-end” harness with no padding and no sizing scheme (one-size-fits-all), with a manufacturer’s suggested retail price (MSRP) of approximately $50; (2) a “mid-range” harness containing only minimal shoulder padding, additional adjustability features, and a universal-fit sizing scheme, with MSRP of approximately $100; and (3) a “high-end” fully adjustable harness with a sizing scheme observing Hsiao’s (2007) guidelines, and advanced comfort-oriented padding, with MSRP of approximately $300 (Figure 2.14). Each harness was tethered to a self-retracting lifeline (Figure 2.15). This type of lifeline worked similarly to a seatbelt, such that sudden changes in downward force (jerk) prevented the lifeline from retracting further. The lifeline was mounted to the upper portion of the scaled world roof, and workers remained tethered during all roofing task performance.

Figure 2.14: Fall Arrest Harness Selections for In-Lab Test System

Figure 2.15: Self-Retracting Lifeline for In-Lab Test System

Participants were instructed to perform simulated construction tasks upon a raised platform while wearing each of the three harnesses. The platform was sloped similarly to residential roof, constructed of 6/12 trusses. The method of construction for the scaled world roof (Figure 2.16) was previously evaluated by Angles et al. (2012b). Figure 2.16 corresponds to a scaled world roof built atop a mechanical truss testing system. Though otherwise construction of the environment remained consistent with the previously studied environment, this iteration of the study occurred in an alternative lab. Corresponding with postures inherent to real-world roofing work, this simulated surface provided a working surface on which participants crouched to perform tasks, stood to gather materials, and traversed during task performance.

Figure 2.16: In-lab Scaled World Roof

Angles et al. (2012a) performed a full task analysis of roof construction during roofing construction phases. Three tasks were chosen as representative tasks that could be represented in a laboratory environment. Each task represents a sub-task of the roofing process in typical residential construction. As time constraints limited plausible demands to impose upon participants in terms of aligning heavy components, the trusses were pre-set in the lab. Installation of OSB sheathing is the sole task representative of frame construction. The two subsequent tasks represent post-frame construction as participants install courses of underlayment and shingles.

2.5 Procedures

Procedures facilitated each of the project goals, including quantifying physical characteristics of tension in harnesses, discovering statistical relationships of EMA-based self-reports with harness pressure, analyzing the differences of self-reports and pressure profiles among different harnesses, and formulating requirements based on the findings within the previous three goals.

Counterbalancing was used to determine order of harness wear. Participants were measured and fitted for each harness. Participants were then instructed to stand quietly for 10 seconds to perform a baseline reading of harness tensions. In a similar manner, the participant was instructed to statically crouch for 10 seconds, as he would while hammering a nail into the floor. Finally, the participant was instructed to walk back and forth along a line on the lab floor for 10 seconds. These three trials represented the "quiet" set of tasks performed prior to roof work. Momentary assessments were gathered as participants rated shoulder and thigh discomfort on a scale of 1 – 10 upon completion of each quiet task, with 1 as the level of baseline comfort experienced while standing quietly without a harness, and with 10 representing very high discomfort such that the harness should be re-adjusted.

Following completion of quiet tasks, each participant installed one course of OSB sheathing, one sheet of underlayment, and two horizontal rows of shingles. These tasks represented the "roofing" set of tasks. Momentary assessments for shoulder and thigh discomfort were collected as during quiet trials, but at an interval of once every 60 seconds, at the occurrence of one of a pre-defined list of salient critical incidents, and immediately upon completion of each task. Critical incidents observed are delineated in Table 2.1

Table 2.1: Salient Critical Incidents Observed During Trials

1. Lifeline makes contact with participant's head or neck	5. Participant drops tool
2. D-Ring position shifts outside of shoulder blades	6. Participant slips
3. Participant manually adjusts lifeline	7. Participant falls
4. Participant manually adjusts harness	8. Participant verbally complains regarding comfort or any component of fall protection system

Three scaled questions were administered were administered at the completion of each harness trial to permit for free-response observations and suggestions regarding harness discomfort. The questions included:

(1) How do you rate the difficulty of adjustment of this harness?

[1: not at all difficult – 10: Very difficult]

(2) How do you rate the fit of this harness?

[1: not a good fit – 10: very good fit]

(3) How do you rate the overall discomfort of this harness?

[1: not uncomfortable – 10: very uncomfortable]

In addition, three open-response prompts were administered at the completion of each harness trial, including:

(1) Please explain any problems you may have encountered due to this harness (comfort, design, fit, etc.)

(2) What other observations did you have about using this fall arrest harness?

(3) What suggestions do you have for improving the design of this fall arrest harness?

Participants were familiarized with the protocol to provide discomfort ratings on a scale of 1 - 10 prior to data collection. For this purpose, an adapted Borg Rating Perceived Exertion Scale was used (Borg, 1998). A printed rating scale was maintained on the laboratory wall for quick reference during task performance, as follows:

0) Nothing at all

0.5) Extremely Weak (just noticeable) Discomfort

1) Very Weak Discomfort

2) Weak Discomfort

3) Moderate Discomfort

4)

5) Strong Discomfort

6)

7) Very Strong Discomfort

8)

9)

10) Extremely Strong (almost maximum) Discomfort

Examples of scenarios corresponding to the rating scale were provided. A computer-generated beep prompted participants to give their integer-number ratings for shoulder and thigh discomfort. The beep prompted a response upon completion of each 60 seconds of work. In addition, a remotely controlled switch was used to manually trigger a computer beep upon critical incident occurrence, thus prompting additional discomfort ratings.

2.6 Outcome Measures

Objective Measures

Pressure: An empirical cumulative density function was generated to represent pressure readings for each participant, from each trial and harness and from each sensor. The 95th percentile of pressure was recorded separately from each quiet trial, and from each roofing trial, by participant and by harness. Subsequently, the mean 95th percentile pressure was found by harness and by participant, separately for quiet and roofing trials. The mean 95th percentile variables were used in further analysis.

Critical Incident Frequency: The total number of critical incident occurrences was recorded by participant and by harness.

Anthropometrics: Anthropometrics data were collected for each participant, including participants' age, weight (lbs), height (in), and years of experience in both general construction and in residential roofing.

Fit: A binary variable (0: non-fit; 1: fit) described whether each harness fit each participant, using a subset of Hsiao's (2003) criteria for harness fit. The subset excluded criteria that required special instrumentation, and criteria requiring suspension above ground. Thus the adapted fit criteria were as follows: (1) Back D-Ring fit between shoulder blades when standing erect, (2) two fingers fit snugly between thigh strap and thigh, (3) shoulder straps fit in center of shoulder, not touching the neck and not slipping off the sides, (4) rear thigh strap fit in the crease between participant buttocks and thigh, and (5) chest strap fit immediately below sternum. Failure in any of the fit criteria led to a zero score for the binary variable.

Subjective Measures

EMA-based Discomfort Ratings: Discomfort ratings were recorded as previously described, separated by shoulder ratings and thigh ratings. The mean rating for both shoulders and thighs was recorded by participant and by harness, separated by quiet trials and roofing trials.

Questionnaire Responses: Numeric responses were collected for each participant and each harness regarding measures of perceived fit, discomfort, and adjustment difficulty, as previously described. Additionally, open-response questions were administered to be considered for recommendations, but were not statistically analyzed.

2.7 Statistical Analysis of Data

Friedman tests (α = .05) were used to statistically test for differences in mean 95th percentile pressure, and differences in all numerically represented subjective measures between harness type. Post-hoc Wilcoxon signed-rank tests with Holm-Bonferroni adjustments were conducted to establish significance in observed differences. Pearson product-moment correlation coefficients were used to examine relationships among all numerically represented subjective and objective measures, except for comparisons with the binary fit variable. Point-biserial correlations were conducted in all tests considering binary fit variables. SPSS® was used to perform all statistical analyses. In addition to examining statistical analyses, post-task interview responses and verbal feedback during task performance were analyzed to determine recommendations for future harness designs.

3. Results

3.1 Comparison of Participant Anthropometrics with General Population

Average participant height and weight were compared against population means of males over age 20 (CDC, 2012). Similarly, participant age was compared against average age of U.S. construction workers (Welch, 2008). Two-tailed t-tests ($\alpha = 0.05$) were conducted to determine whether significant differences existed between participant anthropometrics and population anthropometrics for the three measures considered. Each analysis tested the null hypothesis H_0: there was no significant difference between mean population variable and mean participant measure, against the alternative hypothesis Ha: there was a significant difference between population and participant means.

Table 3.1: Participant Anthropometrics vs. Population averages

Measure	Participant Mean (SD)	Population Mean	t(17)	p-value
Height (in.)	68.9 (2.46)	69.3	-0.613	0.548
Weight (lbs.)	179.7 (30.63)	195.5	-2.184	0.043
Age (years)	36.8 (9.37)	40.4	-1.640	0.119

Thus it was considered that there was no difference in participant height and age when compared against the population mean. However, it appears that mean participant weight was significantly different from the population mean.

3.2 Quiet Trials – Pressure Correlations

Average 95th percentile shoulder and thigh pressure were compared with average EMA-based discomfort ratings by conducting Pearson correlations. Significant findings are summarized in Table 3.2.

Table 3.2: Correlations of Average 95th Percentile Harness Pressure with Discomfort Ratings

Variable 1	Variable 2	Pearson Correlation (N = 54)	p-value
Shoulder Pressure	Thigh Pressure	0.435	0.001
Shoulder Pressure	Periodic shoulder discomfort	0.468	0.000
Shoulder pressure	Periodic thigh discomfort	0.299	0.028

3.3 Quiet Trials – Multiple Comparisons

Friedman tests were conducted on average 95th percentile shoulder and thigh pressure for quiet trials. There was statistically significant difference in 95th percentile shoulder pressure depending on which harness was worn, $\chi^2(2) = 7.000$, $p = 0.030$. Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Holm-Bonferroni correction applied, resulting in ascending significance levels set at $p < 0.017$, $p < 0.025$, and $p < 0.05$. Median (IQR) shoulder pressure levels (in PSI) for harnesses 1, 2, and 3 were 0.6205 (0.3017 to 0.8830), 0.7142 (0.3653 to 1.2734), and 0.4735 (0.2517 to 0.7737). No significance was found between harnesses 3 and 1 ($z = -1.154$, $p = 0.248$). However, there was a statistically significant reduction in shoulder pressure between harness 3 and harness 2 ($z = -2.678$, $p = .007$), and between harness 2 and harness 1 ($z = -2.330$, $p = 0.020$). Thus it is considered that the shoulder pressure resulting from the wear of harness 2 was greater than the shoulder pressure resulting from wear of harnesses 1 and 3.

Additionally, there was statistically significant difference in 95th percentile thigh pressure depending on which harness was worn, $\chi2(2) = 23.412$, $p = 0.000$. Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Holm-Bonferroni correction applied, resulting in ascending significance levels set at $p < 0.017$, $p < 0.025$, and $p < 0.05$. Median (IQR) thigh pressure levels (in PSI) for harnesses 1, 2, and 3 were 0.3622 (0.2479 to 1.3191), 1.0521 (0.7519 to 2.3383), and 0.7958 (0.3039 to 1.5764). No significance was found between harnesses 3 and 1 ($z = -2.107$, $p = 0.035$). However, there was a statistically significant reduction in shoulder pressure between harness 3 and harness 2 ($z = -2.678$, $p = .007$), and between harnesses 1 and 2 ($z = -3.375$, $p = 0.001$). Thus it is considered that both thigh and shoulder pressure measurements were highest in harness 2. No Significance was found when comparing subjective ratings of thigh and shoulder discomfort across harness types.

3.4 Roofing Trials – Correlation of Anthropometrics, Pressure, and Critical Incident Frequency

Average 95^{th} percentile shoulder and thigh pressure, anthropometrics data, frequency of critical incidents, and periodic ratings were compared using Pearson correlations. Pressure and discomfort ratings were considered both by harness, and as averages across all harnesses. Significant results appear below (Table 3.3).

Table 3.3: Significant Pearson Correlations within Roofing Trial Data
* Point-biserial correlation

Variable 1	Variable 2	Pearson Correlation	N	p-value
Weight	H1 Thigh pressure	0.575	18	0.012
Weight	CI Occurrence Frequency H1	-0.542	18	0.020
Total Average Thigh Pressure	Total Average Shoulder Pressure	0.383	54	0.004
Total Average Thigh Discomfort Rating	Total Average Shoulder Discomfort Rating	0.753	54	0.000
H2 thigh pressure	H2 Fit	-0.630*	18	0.005*

3.5 Roofing Trials – Multiple Comparisons

There was statistically significant difference in average 95th percentile shoulder pressure depending on which harness was worn, $\chi2(2) = 7.444$, $p = 0.024$. Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Holm-Bonferroni correction applied, resulting in ascending significance levels set at $p < 0.017$, $p < 0.025$, and $p < 0.05$. Median (IQR) shoulder pressure levels (in PSI) for harnesses 1, 2, and 3 were 0.6675 (0.4509 to 1.3046), 0.7621 (0.4839 to 1.5727), and 0.4271 (0.3523 to 1.1897). No significance was found between harnesses 3 and 1 ($z = -0.414$, $p = 0.679$). However, there was a statistically significant reduction in shoulder pressure between harness 3 and harness 2 ($z = -2.940$, $p = .003$), and between harness 2 and harness 1($z = -2.286$, $p = 0.022$). Thus it is considered that the shoulder pressure resulting from the wear of harness 2 was greatest. This finding is consistent with the results of the static trials.

Likewise, statistical significance was found in average 95th percentile thigh pressure depending on which harness was worn, $\chi2(2) = 12.111$, $p = 0.002$. Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Holm-Bonferroni correction applied, resulting in ascending significance levels set at $p < 0.017$, $p < 0.025$, and $p < 0.05$. Median (IQR) thigh pressure levels (in PSI) for harnesses 1, 2, and 3 were 1.4271 (0.6719 to 2.4627), 3.4180 (2.1110 to 6.0208), and 1.2152 (0.4277 to 2.3617). No significance was found between harnesses 3 and 1 (z = -0.109, p = 0.913). However, there were statistically significant reductions in thigh pressure between harness 3 and harness 2 (z = -3.071, p = .002), and between harness 2 and 1 (z = -3.152, p = 0.002). Thus it is considered that the highest thigh pressure measurements were obtained from harness 2. This finding was also consistent with the results of the static trials.

No significant difference was detected in subjective EMA-based ratings of shoulder and thigh discomfort among the three harnesses. All multiple comparisons of discomfort ratings and average 95th percentile pressure in roofing tasks were consistent with results of corresponding tests in quiet trials.

3.6 Questionnaire Response Correlations

Numerically represented questionnaire responses were compared to determine presence of relations between questions. Questionnaire items measured as follows: [Q1] adjustment difficulty (not difficult – very difficult); [Q2] Fit (not good – very good; and [Q3] Discomfort (not uncomfortable – very uncomfortable). Pearson correlations among variables resulted as follows (Table 3.4).

Table 3.4: Questionnaire Response Correlations

Variable 1	Variable 2	Pearson Correlation (N = 54)	p-value
Adjustment difficulty	Perceived Fit	-0.688	0.000
Adjustment difficulty	Discomfort	0.455	0.001
Perceived Fit	Discomfort	-0.466	0.000

Negative correlation between Q1 and Q2 shows that harnesses were perceived to have a poorer fit as difficulty of adjustment increased. Significance between Q1 and Q3 shows that over-all discomfort increased as the perception of difficulty in adjustment increased. The negative correlation between Q2 and Q3 represents an increase in over-all discomfort as harnesses were perceived to have a poorer fit.

Following, Pearson correlations were run between questionnaire responses and average shoulder and thigh ratings during roofing trials (Table 3.5).

Table 3.5: Correlation of Questionnaire Responses with Discomfort Ratings

Questionnaire Response	Average Periodic Discomfort Rating	Pearson Correlation (N = 54)	p-value
Adjustment Difficulty	Shoulder	.394	.003
Adjustment Difficulty	Thigh	.363	.007
Fit Perception	Shoulder	-.274	.045
Discomfort	Thigh	.535	.000

Results show that as participants perceived harnesses as more difficult to adjust, both shoulder and thigh periodic discomfort ratings increased. Poorer harness fit was perceived as periodic shoulder discomfort increased. Finally, over-all discomfort increased as periodic thigh discomfort ratings increased. No significance was found between periodic shoulder discomfort and over-all discomfort ratings in roofing trials.

Similarly, a correlation of questionnaire responses were conducted with critical incident triggered average discomfort ratings. CI-triggered discomfort ratings were collected at the occurrence of any of the set of pre-defined critical incidents, and were collected separately from the periodic ratings analyzed above (Table 3.6).

Table 3.6: Correlations of Critical Incident-Triggered Discomfort Ratings with Questionnaire Responses

Questionnaire Response	CI-Triggered Average Discomfort Rating	Pearson Correlation (N = 54)	p-value
Adjustment Difficulty	Shoulder	.396	.004
Adjustment Difficulty	Thigh	.423	.002
Fit Perception	Shoulder	-.348	.013
Fit Perception	Thigh	-.321	.023
Discomfort	Thigh	.564	.000

Results of the CI-triggered ratings were largely similar to periodic ratings regarding their relations to questionnaire responses. One exception was the finding of significance between thigh discomfort ratings and the second questionnaire response, suggesting a relation between poorer harness fit and higher thigh discomfort.

The binary fit variable based on Hsiao (2007) criteria was compared against questionnaire responses across all harnesses (Table 3.7). Point-biserial correlations were used to accommodate comparison of questionnaire data against a binary variable.

Table 3.7: Correlations of Fit with Questionnaire Responses

Variable 1	**Variable 2**	**Point-biserial Correlation (N = 54)**	**p-value**
Adjustment Difficulty	Fit	-.291	.032
Fit Perception	Fit	0.303	0.026
Discomfort	Fit	-.272	0.047

Results of the fit-questionnaire correlations suggest that poor fit occurred as difficulty of adjustment increased. Perception of fit (Q2) and actual fit were positively correlated, and perception of discomfort decreased when fit was confirmed.

3.7 Questionnaire Multiple Comparisons

All three numerically represented questionnaire responses were compared by harness using Friedman tests. There was statistically significant difference in questionnaire response for question 1: "How do you rate the difficulty of adjustment of this harness", from 1 (not at all difficult) to 10 (very difficult), depending on which harness was worn, $\chi2(2) = 13.935$, $p = 0.001$. Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Holm-Bonferroni correction applied, resulting in ascending significance levels set at $p < 0.017$, $p < 0.025$, and $p < 0.05$. Median (IQR) questionnaire responses for harnesses 1, 2, and 3 were 5.50 (3.75 to 8.00), 2.00 (1.75 to 3.50), and 2.50 (1.00 to 6.00). No significance was found between harnesses 3 and 2 ($z = -0.109$, $p = 0.913$). However, there were statistically significant reductions in questionnaire response between harness 3 and harness 1 ($z = -2.660$, $p = .008$), and between harness 2 and 1 ($z = -3.190$, $p = 0.001$). Thus it is considered that the harness rated as most difficult to adjust was harness 1.

Likewise, there were statistically significant differences in questionnaire response for question 2: "How do you rate the fit of this harness", from 1 (not a good fit) to 10 (very good fit), depending on which harness was worn, $\chi2(2) = 7.897$, $p = 0.019$. Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Holm-Bonferroni correction applied. Median (IQR) questionnaire responses for harnesses 1, 2, and 3 were 5.00 (2.75 to 6.25), 6.00 (5.00 to 8.25), and 8.00 (5.00 to 9.00). No significance was found between harnesses 2 and 1 ($z = -2.114$, $p = 0.035$) or between harnesses 3 and 2 ($z = -1.191$, $p = 0.234$). However, there was a statistically significant reduction in questionnaire response between harness 3 and harness 1 ($z = -2.423$, $p = .015$). Thus it is considered that the harness 3 was rated to fit better than harness 1.

Finally, statistical significance was detected in the difference of responses for question 3: "How do you rate the over-all discomfort of this harness", from 1 (not uncomfortable) to 10 (very uncomfortable), depending on which harness was worn, $\chi2(2) = 6.400$, $p = 0.041$. Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Holm-Bonferroni correction applied. Median (IQR) questionnaire responses for harnesses 1, 2, and 3 were 5.50 (3.75 to 7.25), 5.00 (3.00 to 6.00), and 3.00 (2.00 to 5.25). No significance was found between harnesses 3 and 1 ($z = -2.048$, $p = 0.041$) or between harnesses 3 and 2 ($z = -1.540$, $p = 0.124$). However, there was a statistically significant reduction in questionnaire response between harness 3 and harness 1 ($z = -2.653$, $p = .008$). Thus it is considered that the harness 1 was rated to cause more discomfort than harness 3.

3.8 Harness Fit Multiple Comparison

The binary variable of fit based on the Hsiao (2007) non-suspended state standards was compared across harnesses using a Friedman test. There was a statistically significant difference in the binary results of harness fit criteria, depending on which harness was worn, $\chi2(2) = 21.733$, $p = 0.000$. Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Holm-Bonferroni correction applied, resulting in ascending significance levels set at $p < 0.017$, $p < 0.025$, and $p < 0.05$. Median (IQR) questionnaire responses for harnesses 1, 2, and 3 were 0 (0 to 0), 1 (1 to 1), and 1 (1 to 1). No significance was found between harnesses 3 and 2 ($z = -1.732$, $p = 0.083$). However, there was a statistically significant reduction in questionnaire response between harness 2 and harness 1 ($z = -3.051$, $p = .002$), and between harness 3 and harness 1 ($z = -3.742$, $p = 0.000$). Thus it is considered that the participants were least able to comply with fit criteria when wearing harness 1, while there was no significant difference between fit criteria compliance when wearing harnesses 2 and 3.

3.9 Harness Fit: Correlation with Pressure

Average 95^{th} percentile thigh pressure in harness 2 and the binary fit variable of harness 2 were negatively correlated, $r(16) = -0.630$, $p = 0.005$, suggesting that participants who met harness 2 fit criteria worked with lower thigh strap pressure in the harness. No other significant correlations were detected between fit and pressure.

3.10 Anthropometrics Correlations

Correlations of anthropometrics data against average 95^{th} percentile pressure were performed using Pearson's product-moment correlation coefficient. Weight and 95^{th} percentile of thigh pressure encountered during use of harness 1 were positively correlated, $r(16) = 0.575$, $p = 0.012$, suggesting that the thigh straps of this harness were more closely worn among heavier participants. Additionally, 95^{th} percentile thigh pressure in harness 2 and the binary fit variable of harness 2 were negatively correlated, $r(16) = -0.538$, $p = 0.021$, suggesting that participants who met harness 2 fit criteria worked with lower thigh strap pressure in the harness. No significant interactions were detected between 95th percentile shoulder pressure and anthropometrics data.

4. Discussion

The purpose of this study was to compare features of three different fall arrest harnesses in terms of user perceptions and physical attributes, and to create recommendations for future harness design supported by comparison findings. Four research objectives were devised to analyze harnesses. The first objective was to develop a system to quantify harness strap pressure. The following objective was to analyze the relationship of strap pressure with self-reported EMA-based usability metrics. The third objective was to analyze comparisons across harnesses considering EMA reports, strap pressure, and questionnaire responses. Finally, features that emerged as significant contributors to fit and discomfort were considered in creating design requirements for future harnesses. The objectives are discussed respectively in sections 4.1 – 4.4.

4.1 Objective 1: Develop a Pressure Quantification System

The system of pressure quantification previously described was successfully implemented throughout all trials. To streamline the calibration process, the same sensors were generally used in the same locations across all harnesses and across all participants. However, occasionally sensors developed short circuits as repeated use led to shifting or wear of resistive textile layers. This occurrence was immediately obvious upon beginning the calibration process, and the sensors were replaced in such instances. Therefore, backup sensors were retained at all times. The process of creating sensors was somewhat streamlined to accommodate for replication.

The primary limitations of the pressure measurement system were the relatively short lifespan of sensors, and their lack of ability to retain a calibration profile throughout multiple trials.

However, these disadvantages were offset by the exceedingly low cost of the system when compared with commercially available pressure measurement systems. For future use, it would be of benefit to examine more precise methods of sensor manufacturing, or consider use of a commercial system if such funding is available.

4.2 Objective 2: Analyze Relation of Discomfort Ratings and Harness Pressure

The presence of relation between periodic EMA-based discomfort ratings and harness pressure varied depending upon the activity type of participants. For example, in quiet trials, shoulder pressure was found to be significantly correlated with discomfort ratings of both shoulders and thighs. However, in roofing trials, no correlation between pressure and discomfort ratings existed. The presence of a relation between shoulder pressure and discomfort in quiet trials may be explained by the constant participant contact of shoulder straps during those trials. As no lifeline was attached during quiet trials, no tension was present to remove harness straps from the participants' shoulders. However, a lifeline maintained the shoulder straps in a state of tension for the duration of all roofing tasks. Therefore, the straps often failed to retain contact with participants' shoulders. Thus shoulder harness strap pressure during dynamic tasks may not be an indicator of participant discomfort.

Although a positive correlation existed between shoulder and thigh pressure for both task types, thigh pressure was not significantly correlated with periodic discomfort ratings for quiet or roofing tasks. Lack of findings regarding thigh pressure may be due to the location of thigh sensors. To remain unobtrusive, sensors were placed touching participants' outer thighs. However, some participants explained the presence of discomfort in the groin area, suggesting that measurement of inner thigh pressure might be a stronger indicator of discomfort. The trade-off of this approach would be risking more obtrusive instrumentation that might confound results, as the instrumentation itself may contribute to discomfort.

Due to non-normality of data, multiple comparisons were conducted using Friedman tests with post-hoc Holm-Bonferroni corrected comparisons. Use of this method has been previously validated for application in biomechanical evaluation of pressure measures (Gerhard et al., 2011). When considering such comparisons for shoulder and thigh strap pressures, highest measures of both areas were found in harness 2 for both quiet and roofing trials. There was no significant difference in pressure measures in harnesses 1 and 3.

Higher pressure in harness 2 may be explained by a combination of fit and level of padding. The high level of padding in harness 3 may have reduced strap pressure at the sensor measurement areas. Lin et al. (1996) explained that the presence of strap padding in satchels provided friction to reduce slippage. In the context of fall arrest harnesses outfitted with pressure sensors, slippage could cause undue variations in sensor readings. Although harness 1 contained no padding, its strap pressure may have been reduced due to relatively poor fit. Multiple comparisons showed that harness 1 fit significantly less participants than the other two harnesses. For context, the harness fit only four participants, or about 22% of the participant pool. The most immediately obvious cause of fit criteria failure in harness 1 was D-ring positioning. As harness 1's shoulder straps were non-adjustable, the harness remained in a slack position on smaller participants, lending to low strap pressure.

Aside from the aforementioned significant correlation of shoulder pressure with discomfort ratings in quiet trials, no further relationship of strap pressure and discomfort was detected. Quiet trial findings may not be applicable to quasi-naturalistic harness testing, as no lifeline could be worn, and construction tasks would not be well facilitated if only quiet conditions were tested. Thus it is considered that factors other than pressure may have influenced discomfort.

4.3 Objective 3: Analyze Differences in Subjective Feedback among Harnesses

EMA-Based Discomfort Ratings

When performing multiple comparison tests, there was no significant difference in mean periodic shoulder or thigh discomfort ratings for any of the harnesses in quiet or roofing tasks. The lack of findings by this analysis calls the validity of EMA-based periodic ratings into question for this application. The length of time spent wearing harnesses may not have been sufficient to induce discomfort as encountered on job sites.

Questionnaire Responses

To reiterate, questionnaire items included: [Q1] adjustment difficulty (not difficult – very difficult); [Q2] Fit (not good – very good; and [Q3] Discomfort (not uncomfortable – very uncomfortable). All three questionnaire responses were significantly correlated, suggesting interrelations between adjustments, fit, and discomfort of fall arrest harnesses. Specifically, perception of higher adjustment difficulty (Q1) was associated with perception of poorer fit (Q2) and greater discomfort (Q3), and perception of poorer fit was associated with greater discomfort.

Difficulty of adjustment was significantly, positively correlated with both shoulder and thigh EMA-based discomfort ratings, in both periodic and critical incident-triggered collections. As participants encountered more difficulty adjusting harness straps, non-optimal fits may have occurred. Even in instances where all fit criteria were met, lack of ability to fine tune adjustments in certain straps may have led to higher perception of discomfort. For example, participants generally unfastened thigh straps from harness 1 prior to adjusting due to its looping adjustment mechanisms (Figure 4.1). In contrast, harness 2 used a belt-like mechanism for adjustment of thigh straps, which permitted adjustment during wear (Figure 4.2). Harness 3 used a similar mechanism to harness 1, but with the addition of a locking feature. When the mechanism was placed into the "unlock" position, the strap moves freely and may be adjusted during wear (Figure 4.3).

Figure 4.1: Harness 1 Thigh Strap Adjustment

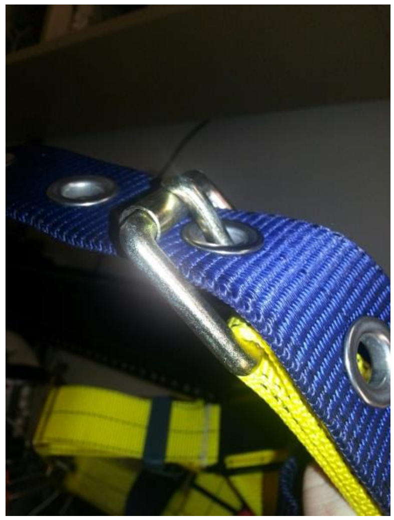

Figure 4.2: Harness 2 Thigh Strap Adjustment

Figure 4.3: Harness 3 Thigh Strap Adjustment

Multiple comparisons regarding perception of fit (the first questionnaire response, Q1) showed that participants perceived harness 1 as most difficult to adjust, while there was no detectable difference between harnesses 2 and 3. The thigh strap adjustment mechanism previously mentioned was most likely a strong contributing factor. However, upper body adjustments may have influenced the variable as well. While harnesses 2 and 3 were outfitted with vertically adjustable upper body straps, harness 1 did not have vertical adjustability (Figures 4.4 – 4.6). Adjustment pieces in harnesses 2 and 3 were fully adjustable during wear, allowing for relatively simple adjustment (Figure 4.7). Harness 1's lack of vertical strap length adjustability may have been a contributing factor to the relatively poor fit of the harness. However, all three harnesses were outfitted with vertically adjustable cross-chest straps, lending to simple fit compliance for the chest strap placement criterion.

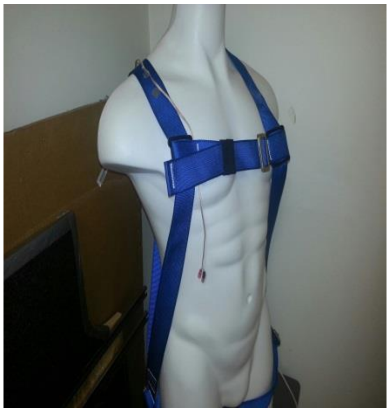

Figure 4.4: Harness 1 Upper Body
(No Vertical Adjustment)

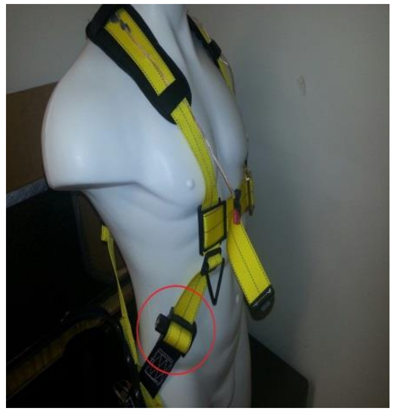

Figure 4.5: Harness 2 Upper Body
(Vertical Adjustment Circled)

Figure 4.6: Harness 3 Upper Body
(Vertical Adjustment Circled)

Figure 4.7: Vertical Strap Length Adjustment Mechanism

The Hsiao-based (2003) fit criteria variable was negatively correlated, $r(54) = -0.291$, $p = 0.032$, with perception of adjustment difficulty, suggesting that better fit was associated with the perception of non-difficult adjustment. One implication of the finding is that usable adjustments may be more than a personal preference, as some users may not be able to adjust a harness to fit properly if its adjustment mechanisms are difficult to use.

Multiple comparisons of the second questionnaire response (Q2), regarding perception of harness fit, showed that participants perceived harness 3 to fit significantly better than harness 1. No significant differences were detected regarding harness 2. Fit compliance rates were 22.2% with harness 1, 83.3% with harness 2, and 100% with harness 3. The lack of significance between perception of fit in harnesses 1 and 2 was notable, suggesting that participant criteria for fit may not have aligned with objective fit criteria. However, the perception of fit and the binary variable of fit criteria compliance were positively correlated, $r(54) = 0.303$, $p = 0.026$, suggesting that some participants were able to accurately judge whether the harness fit them.

Q2 was negatively correlated with average EMA-based shoulder discomfort ratings for both periodic and critical-incident triggered collections, suggesting that better fit was perceived when discomfort in the shoulders was low. Additionally, a significant negative correlation was detected between perception of fit and CI-triggered thigh discomfort ratings. As many of the CI-triggered ratings were collected during instances that exemplified poor fit (for example, manual adjustment of the harness, or D-ring shifts), the emergence of this significance was not unexpected. Lower thigh pressure may have occurred in participants who were unable to adjust the thigh strap length as short as needed. As shown in anthropometrics analysis, the participant pool weighed significantly less on average than the general population. Chen et al. (2011) found a significant relation between thigh muscle volume and body mass. Thus, participants in this study may have had smaller thigh muscle mass than the general population, lending to a need for shorter thigh straps than the harnesses could feasibly accommodate.

In general, it appears that low participant weight may have been associated with poor experience in the use of harness 1, and weight may have been a contributor to over-all poor fit of the harness. In particular, low weight was significantly correlated with higher frequency of critical incident triggers during use of harness 1, suggesting poor fit during dynamic movement as previously discussed. As mean participant weight was determined to be significantly lower than mean population weight, the over-all experience of use in the harness may have been negatively skewed due to association with poor fit.

The third questionnaire response gauged perception of over-all discomfort encountered during wear of each harness. The perception of discomfort in harness 1 was rated significantly higher than the discomfort encountered in harness 3, while no significant differences were detected regarding harness 2. The difference in perception was likely a combination of fit, adjustment features, and padding. Harness 3 was fitted to participants by size, was fully adjustable, and featured extensive padding, while harness 1 was universally sized, had few adjustment features, and no padding. When compared with harness 2, containing a universal size, full adjustment features, and moderate padding, the advantages of harness 3 appear to be primarily in the extensiveness of padding, and the adoption of a sizing scheme.

Perception of over-all discomfort (Q3) was significantly, positively correlated with thigh discomfort ratings for both periodic ($r(54) = 0.535$, $p = 0.000$) and CI-triggered ($r(54) = 0.564$, $p = 0.000$) responses during roofing trials. However, there was no significant relation of over-all perception of discomfort (Q3) with EMA-based shoulder discomfort ratings. Thus thigh discomfort appeared to be a greater indicator of over-all discomfort perception than shoulder discomfort. A likely cause for this finding is the constant state of shoulder strap tension caused by the attachment of a retractable lifeline, preventing shoulder straps from making participant contact. Lifeline tension would not have had as great an effect on thigh strap movement.

While the perception of discomfort was significantly negatively correlated with perception of better fit ($r(54) = -0.466$, $p = 0.000$), there was no significant relation between perception of discomfort and compliance with fit criteria. This finding suggests that while comfortable features may have led participants to believe a harness fit better, there was no true difference in fit based on comfort.

Free Responses

Three free-response format questions were asked in each questionnaire, administered after all trials associated with each harness. Free-response prompts included: [1] "Please explain any problems you may have encountered due to this harness (comfort, design, fit, etc.)." [2] "What other observations did you have about using this fall arrest harness?" and [3] "What suggestions do you have for improving the design of this fall arrest harness?" As specified in the IRB protocol, all responses were optional, and not all participants elected to respond to all free response prompts. Feedback gathered in the free-response section was used to find anecdotal support for generalized findings regarding over-all perception of the three harnesses.

Of positive comments gathered regarding harness 1, many focused on the "light weight" of the harness. However, harness 1 feedback was largely negative. Specifically, participants commented that the harness was "difficult to adjust" and that "adjustment takes longer". The harness did not accommodate adjustments for all participants, as evidenced previously by fit criteria findings. Some comments provided further insight to suggest that the harness may have been "made for larger workers," suggesting a design for the upper extreme. Furthermore, the participants' initial adjustments may not have withstood the stresses placed on the harness by roofing activities, as one participant indicated the harness "became sloppy and didn't fit as well as I [continued] working". Redesign suggestions for the harness generally focused on adjustment features ("add quick adjustment mechanisms") and comfort-oriented features ("add padding").

Comments on harness 2 were generally sparser than responses for the other two harnesses, though the general tone of responses was positive. Informally, many participants suggested that their daily use harnesses were most similar to harness 2. Positive harness 2 responses also mentioned its "light weight". Participants noted that it was "relatively comfortable" and a "good fit", while it was "simple to adjust". In terms of criticisms, participants suggested the harness "needs more padding in pressure areas," specifically as the harness "cramps the crotch".

Participants again commended the fit of harness 3 ("fits well"), and were generally satisfied with the adjustment mechanisms ("like the adjustment features"). However, one participant indicated that the "strap lock mechanism is complicated for inexperienced roofers," suggesting that a learning curve may be associated with the locking feature of harness 3's adjustments. Although participants called for more padding on the other two harnesses, comments suggested to "reduce padding" on harness 3. The justification for this suggestion was often the weight, as participants complained that the "heavy pads" were "hot" and one participant complained that it "makes [him] sweat". Participants suggested that the harness would "absorb sweat and will start to smell bad" and suggested that the harness should be "more lightweight".

4.4 Objective 4: Develop Design Requirements for a Desirable Harness

Harness Weight

A major theme of comments across all three harnesses appeared to be a focus on harness weight. Participants evidently valued lightweight harnesses, likely due to high heat working conditions. Thus the harness should be as lightweight as possible, while still incorporating all other required features. While the difference in harness mass was seemingly small (approximately 1.0 kg for the lightest, harness 1, and approximately 2.0 kg for the heaviest, harness 3 in size large), the difference was evidently detectable by participants. Interestingly, there were no negative comments on weight regarding harness 2, which at 1.8 kg, weighed only marginally less than harness 3. This would suggest that either the threshold for weight discomfort is 2.0 kg, or more likely, that the volume of padding influences perception of harness weight.

Harness Padding

Participants appeared to value padding in harnesses. Harness 3 (with heavy padding) was rated as significantly more comfortable than harness 1 (with no padding). Comments suggested that participants desired more padding in both harnesses 1 and 2. However, as previously discussed, padding in harness 3 may have led to perception of high harness weight. Therefore a compromise between padding and weight should be realized on a redesigned harness. The introduction of lightweight, breathable padding, perhaps similar to that found in bicycle shorts chamois, might satisfy user desire for some level of padding in the harness. There appears to be a specific need for padding in the shoulder and groin areas, as evidenced by participant comments. Shoulder padding may carry the additional benefit of adding some level of friction to prevent straps from slipping, lending to better fit compliance during use. The padding should be equipped with soft edges, to prevent further complaints of straps “digging into” users’ bodies, a complaint received regarding the thin nylon-stitched edges of pad inserts on the shoulders of harness 2.

Adjustment Features

Harness 1 was rated significantly more difficult to adjust than the other two harnesses, while few differences were detected in the adjustment mechanisms of harness 2 and harness 3. Additionally, there was no significant difference in the passage rate of harness fit between harnesses 2 and 3, while harness 1 fit significantly worse. Analyses showed that improvements were needed over the adjustment mechanism of harness 1, but the differences between harness 2 and harness 3 were not as evident.

One suggestion that some participants may have preferred the belt-like adjustment mechanism of harness 2 was found in a comment regarding perception of difficulty in the locking adjustment mechanisms of harness 3 (“complicated for inexperienced roofers”). This comment combined with the otherwise general lack of acknowledgement of difference, suggests that there is no disadvantage to a belt-like thigh adjustment mechanism. The mechanism is likely less expensive to manufacture than locking mechanisms, while it is perceived to fit just as well, and did not significantly influence the pass rate of objective fit criteria. Thus a redesigned harness should incorporate a belt-like thigh strap length adjustment mechanism.

Perhaps the largest deficiency leading to over-all poor fit in harness 1 was the lack of a vertical upper body strap length adjustment feature. Lack of this feature was likely the most frequent cause of fit non-compliance, as shoulder straps were consistently too large in the vertical orientation for all but the heavier participants. Therefore, redesigned harnesses should include vertical adjustment components below the shoulders, as found on both harnesses 2 and 3. Both harnesses included a similar rolling mechanism for vertical adjustment. While there were no complaints regarding the mechanism, future studies might consider alternative mechanism types.

Sizing Scheme

Harness 3 was the only sized harness, using a scheme developed by Hsiao et al. (2009). It was the only harness with a 100% fit rate of the participant pool. However, at approximately $300, the harness was significantly more expensive than the comparisons. By multiple comparisons, there was no statistically significant difference in objective fit compliance between harnesses 2 and 3, although harness 2 met fit criteria for only 83.3% of participants. However, both harnesses 2 and 3 conformed to fit criteria significantly better than harness 1, which only accommodated 22.2% of participants. However, the statistically significant difference in mean participant weight vs. mean general population weight may have influenced the fit rate of all harnesses, and conformity with fit criteria may not be an accurate portrayal of the over-all user base of fall arrest harnesses. In consideration of the 100% success rate of harness 3, a three-sized fit scheme should be implemented according to the sizing structure developed by Hsiao et al. (2009), as similar to harness 3. Although the implementation of sizing schemes may increase harness cost, the reduction of padding level and locking adjustments should permit a generally accessible harness with retail price lying between $100 and $300, referenced to harnesses 2 and 3.

5. Conclusions

Findings showed that pressure may not be an indicator of harness strap discomfort during use in roofing tasks. However, findings regarding fit and subjective feedback led to evidence for needed improvements in harness designs. Mid-range and high-end harnesses exhibited clear advantages over a low-end counterpart. However, the level of advantage of a high-end harness over a mid-range harness was ambiguous. There was an apparent advantage for harnesses containing quick-adjustment features and vertically-adjustable shoulder straps. Perception of low weight appeared to influence comfort level, although perception of weight may have been influenced by the volume of padding. Participants indicated preference for padding, but not to the extent found in the high-end harness. The advantage of adopting a sizing scheme as opposed to a one-size-fits-all approach was not as strongly evidenced as predicted, but may have been influenced by an over-all low-mass participant pool. Regardless, 100% fit conformance in a size schemed harness supported that some level of sizing scheme advantage exists.

6. References

Affleck, G., Zautra, A., Tennen, H., and Armeli, S., 1999. “Multilevel daily process designs for consulting and clinical psychology: a preface for the perplexed,” Journal of Consulting and Clinical Psychology 67, pp. 746–754.

Angles, J., Nakata, A., Morris, J., Dhillon, G., Smith-Jackson, T., and Hindman, D., 2012. “Requirements and Task Analysis of Fall Protection for Residential Construction,” Industrial and Systems Engineering Research Conference, Orlando, FL, 19-23 May 2012.

Angles, J., Trochez, G., Nakata, A., Smith-Jackson, T., Hindman, D., and Harold, V., 2012. “A Scaled-World Prototype for Structural and Usability Testing in Residential Construction,” Human Factors and Ergonomics Society 56th Annual Meeting, Boston, MA, October 22-26, 2012.

Bradtmiller, B., Whitestone, J., Feldstein, J., Hsiao, H. and Snyder, K., 2000. “Improving fall protection harness safety: contributions of 3-D scanning,” Proceedings of Scanning 2000: The European Meeting Point for Scanning (Paris, France: Numerisation 3D), 117 – 128

Borg, G., 1998, “Borg’s Perceived Exertion and Pain Scales,” Human Kinetics, Champaign, IL.

Brewer, M., 2000. “Research Design and Issues of Validity,” In Reis, H. and Judd, C. (Eds.). Handbook of Research Methods in Social and Personality Psychology. Cambridge: Cambridge University Press.

Brinkley, J.W., 1988. “Experimental Studies of Fall Protection Equipment,” Proceedings of the 1st International Fall Protection Symposium (Toronto, Canada: International Society for Fall Protection), 51 – 65

Bronfenbrenner, U., 1977. “Toward an Experimental Ecology of Human Development,” American Psychologist, 32, 513–531.

Bryant, J., Doan, J., Stevenson, J., and Pelot, R., 2001. “Validation of Objective Based Measures and Development of a Performance-Based Ranking Method for Load Carriage Systems,” Proceedings of the Soldier Mobility: Innovations in Load Carriage System Design and Evaluation Conference, Kingston, 20 June 2001.

Bryk, A. S., & Raudenbush, S. W., 1992. “Hierarchical linear models,” Newbury Park, CA: Sage.

Center for Disease Control, 2012. “Anthropometric Reference Data for Children and Adults: United States, 2007–2010,” Vital Health Statistics 11:252.

Chen BB, Shih TT, Hsu CY, Yu CW, Wei SY, Chen CY, Wu CH, Chen CY., 2011. “Thigh muscle volume predicted by anthropometric measurements and correlated with physical function in the older adults,” Journal of Nutrition, Health, and Aging 15(6), 433-8.

Christensen, T., Barrett, L., Bliss-Moreau, E., Lebo, K., and Kaschub, C., 2003. “A Practical Guide to Experience-Sampling Procedures,” Journal of Happiness Studies 4:53-78.

Cohen, J., 1992. “A Power Primer,” Quantitative Methods in Psychology 112(1), 155-9.

Ehret, B.D., Gray, W.D. & Kirschenbaum, S.S., 2000. “Contending with Complexity: Developing and Using a Scaled World in Applied Cognitive Research,” Human Factors, 42(1), 8-23.

Ehret, B.D., Kirschenbaum, S.S., & Gray, W.D., 1998. “Contending with Complexity: The Development and Use of Scaled Worlds as Research Tools,” Human Factors and Ergonomics Society 42th Annual Meeting (pp. 254-257). Santa Monica, CA: Human Factors and Ergonomics Society.

Elson, J.L., 2003. “Expert and Novice Performance in an Industrial Engineering Scaled World Simulation,” (Doctoral dissertation). The Ohio State University. Columbus, Ohio.

Feldman, S., Downey, G., & Shaffer-Neitz, R., 1999. “Pain, negative mood, and perceived support in chronic pain patients: A daily diary study of people with relax sympathic dystrophy syndrome,” Journal of Consulting and Clinical Psychology, 67, 000-000.

Feldman Barrett, L. and Barrett, D.J., 2001. "An Introduction to Computerized Experience Sampling in Psychology," Social Science Computer Review 19(2), pp. 175–185.

Gerhard, C., Ohlendorf, D., Betz, W., and Kopp, S., 2011. “Evaluation of foot pressure distribution on dental foot pedals,” Manuelle Medizin, 49 (2), pp. 99-106.

Gray, W.D., 2002. “Simulated Task Environments: The Role of High-Fidelity Simulations, Scaled Worlds, Synthetic Environments, and Laboratory Tasks in Basic and Applied Cognitive Research,” Cognitive Science Quarterly, 2, pp. 205-227.

Hoffman, K. 2001. “Applying the Wheatstone Bridge Circuit,” Hottinger Baldwin Messtechnik GmbH.

Hsiao, H., Bradtmiller, B., and Whitestone, J., 2003. “Sizing and Fit of Fall-Protection Harnesses,” Ergonomics, 46:12, pp. 1233-1258.

Hsiao, H., Friess, M., Bradtmiller, B., & Rohlf, J. (2009). Development of sizing structure for fall arrest harness design. Ergonomics, 52, pp. 1128–1143.

Hsiao, H., Whitestone, J., and Kau, T., 2007. “Evaluation of Fall Arrest Harness Sizing Schemes,” Human Factors: The Journal of the Human Factors and Ergonomics Society, 49:447.

ISO, 2010. “Basic Human Body Measurements for Technological Design Part 2: Statistical Summaries of Body Measurements from Individual ISO Populations,” Standard 7250-2:2010.

Klein, S.B.: 2001, "A Self to Remember: A Cognitive Neuropsychological Perspective on How Self Creates Memory and Memory Creates Self,” in C. Sedikides and M. Brewer (eds), Individual Self, Relational Self, Collective Self (Psychology Press, Philadelphia), pp. 25–46.

LeBlanc, V. R., Manser, T., Weinger, M. B., Musson, D., Kutzin, J., & Howard, S. K., 2011. “The Study of Factors Affecting Human and Systems Performance in Healthcare Using Simulation,” Simulation in Healthcare: The Journal of the Society for Simulation in Healthcare, 6 (7), S24-S29.

Lin, C. J., Dempsey, P. G., Smith, J. L., Ayoub, M. M., Bernard, T. M., 1996. Ergonomic investigation of letter-carrier satchels: Part II. Biomechanical laboratory study,” Applied Ergonomics, 27 (5), pp. 315-320.

Lipscomb, H. J., Dale, A., Kaskutas, V., Sherman-Voellinger, R., and Evanoff, B., 2008. “Challenges in residential fall protection: insight from apprentice carpenters,” American Journal of Industrial Medicine. 51:60-68.

Mackie, H., Stevenson, J., Reid, S., and Legg, S., 2005. “The Effect of Simulated School Load Carriage Configurations on Shoulder Strap Tension Forces and Shoulder Interface Pressure,” Applied Ergonomics, 36, pp. 199-206.

Martin, J. and Hooper, R., 2000. “Military Load Carriage: A Novel Method of Interface Pressure Analysis,” RTO HFM Specialists’ Meeting, Kingston, 27-29 June 2000

Mine Safety Appliances, 2010. “Sizing and Fit of MSA’s EVOTECH™ Fall Protection Harness”

National Instruments, 2006. “Strain Gauge Configuration Types,” NI Supported Tutorial.

NASA Reference Publication 1024, 1978. "Anthropometric Source Book Volume I: Anthropometry for Designers"

Neisser, U., 1976. "Cognition and reality," San Francisco: Freeman.

O'Brien, D., Sottos, N. & White, S., 2007. "Cure-dependent Viscoelastic Poisson's Ratio of Epoxy," Experimental Mechanics, 47:237-239.

Occupational Safety & Health Administration, 2010. Fall protection, construction (29 CFR 1926.501).

Occupational Safety & Health Administration, 2010. Fall Protection Systems Criteria and Practices (29 CFR 1926.501).

Rivera, S. M., Wakeley, A., & Langer, J., 1999. The drawbridge phenomenon: Representational reasoning or perceptual preference? Developmental Psychology, 35, 427–435.

Shiffman, S., Stone, A., and Hufford, M., 2008. "Ecological Momentary Assesssment," Annual Review of Clinical Psychology. 4:1-32

Smith-Jackson, T., Hindman, D., Shields, L., Thomas, B., Gallagher, C., and Koch, L., 2011. "Safety Climate and Use of Fall Arrest Systems," Proceedings of CIB W099 2011, Prevention: Means to the End of Construction Injuries, Illnesses and Fatalities, Washington, D.C., August 24-26, 2011.

Smyth, J. and Stone, A., 2003. "Ecological Momentary Assessment Research in Behavioral Medicine," Journal of Happiness Studies. 4:35-52

Steiger, H., Gauvin, L., Jabalpurwala, S., Seguin, J. R., & Stotland, S., 1999. "Hypersensitivity to Social Interaction in Bulimic Syndromes: Relationship to Binge Eating. Journal of Consulting and Clinical Psychology, 67, pp. 765-775.

Stone A, Shiffman S., 1994. "Ecological Momentary Assessment in Behavioral Medicine," Ann. Behav. Med. 16:199–202

Stone AA, Shiffman S, Atienza A, Nebeling L., 2007. "Introduction to Ecological Momentary Assessment (EMA)."

U.S. Bureau of Labor Statistics, 2011. "2010 Census of Fatal Occupational Injuries (preliminary data), Industry by event or exposure," Retrieved from: http://www.bls.gov/iif/oshwc/cfoi/cftb0250.pdf.

VanLeeuwen, D., 1997. "A note on the covariance structure in a linear model," The American Statistician, 51, pp. 140-144.

Welch, L., 2008. "The Aging Worker in U.S. Construction Industry," Occupational Health and Safety, Exclusively Online: http://ohsonline.com/articles/2010/03/01/the-aging-worker.aspx

APPENDICES

APPENDIX A: Informed Consent

Virginia Polytechnic Institute and State University

Informed Consent Form

Principal and Co-Principal Investigators: Michael Agnew, PhD

Additional Investigators: Daniel Hindman, PhD and Joe Angles

I. PURPOSE

You are invited to participate in a study on Fall Arrest Harnesses for Construction. This study will examine what you think about fall arrest harnesses and systems during and after roofing tasks while measuring strap pressure in the harness. The data collection is expected to take about 2 hours.

II. PROCEDURES

You will be asked to perform the following tasks.

Read and sign an Informed Consent Form (this form).

Allow us to measure your weight on scale and your height.

Receive instructions on the wear and use of a fall arrest harness.

Conduct three short tasks (standing, walking, crouching).

Conduct three roofing-related tasks on a roof setting in this lab while wearing the fall arrest harness. Those three tasks are to install OSB, underlayment, and shingles.

Give feedback about discomfort during the tasks.

Answer questions about the fall arrest system after each task.

Have a short interview after finishing all tasks.

It is important for you to understand that we are <u>not</u> evaluating you or your performance in any way. Your opinions are very valuable to us and will help us to design a better fall arrest system to prevent injuries and deaths from construction falls. Therefore, we ask that you perform normally and be as honest as possible. The information and feedback that you provide is very important to this project.

III. RISKS and BENEFITS

There are risks to you as a participant in this study as follows.

You may experience minor muscle strain as a result of performing the tasks.

You may experience some muscle soreness, 1-2 days after the data collection.

You may experience slipping or falling from the roof setup while performing the tasks.

To minimize the risk of injury to you, we will require that you wear the safety harness. It will be firmly attached to the lifeline on the roof setting, so that if you slip on or start falling from the roof setting, the rope will catch you and we will rescue you immediately.

Participants in a study are considered volunteers, regardless of whether they receive payment for their participation. Under Commonwealth of Virginia law, workers compensation does not apply to volunteers. Appropriate health insurance is strongly recommended to cover these types of expenses.

This research project will help understand usability of the fall arrest harnesses. While this research may yield such a benefit, no promise or guarantee of benefits will be made to you as a participant. Participants may contact the investigators listed at the end of Consent Form to inquire about the results and conclusions of this research.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. No one outside the research team will be able to connect any data with your name. The information you provide will have your name removed and only a three digit participant number will be used during analyses and any written reports of the research. No reference will be made in oral or written reports that could link you to the data nor will you ever be identified as a participant in the study.

VI. COMPENSATION

You will be compensated for $60 upon completion of your participation. You will be paid at the end of this study in cash.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time without penalty or reason stated, and no penalty or withholding of compensation will occur for doing so. If you choose to withdraw, you will be compensated for the portion of time of the study for which you participated. Furthermore, you are free not to answer any question or respond to experimental situations and there is no penalty for your refusal or declinations. There may be circumstances under which the investigator may determine that the experiment should not be continued. In this case, you will be compensated for the portion of the project completed.

VIII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University.

Participant's Acknowledgements

Check in the box if the statement is true:

- □ I am not under the influence of alcohol or drugs.
- □ I have no current or recent (past year) musculoskeletal problems.

PARTICIPANT'S RESPONSIBILITIES

I voluntarily agree to participate in this study. I have the following responsibilities:

1. Read and understand the aforementioned instructions;

2. Answer questions honestly and to the best of my ability;

3. Be aware that I am free to ask questions at any point time;

4. Keep the activities and information discussed confidential, since others will be participating in this study.

XI. PARTICIPANT'S PERMISSION

I voluntarily agree to participate in this study, and I know of no reason I cannot participate. I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project. If I participate, I may withdraw at any time without penalty.

_______________________________________ ___________

Signature Date

_______________________________________ ______________________

Name (please print) Contact: phone number

XIII. CONTACT

If you have questions at any time about the project or the procedures, you may contact the principal investigator, Michael Agnew at (540) 231- 0083 or mjagnew@vt.edu.

If you feel you have not been treated according to the descriptions in this form, or your rights as a participant have been violated during the course of this project, you may contact David Moore, Chair of the Institutional Review Board Research Division at (540) 231-4991.

APPENDIX B: Post-Task Questionnaire

For Each Harness:

1. How do you rate the difficulty of adjustment of this harness?

Not at all difficult				Moderately difficult to adjust					Very Difficult to Adjust
1	2	3	4	5	6	7	8	9	10

2. How do you rate the fit of this harness?

Not a good fit (like wrong clothing size)				Moderately good fit					Very good fit (feels like it was made just for you)
1	2	3	4	5	6	7	8	9	10

3. How do you rate the over-all *discomfort* of this harness?

Not uncomfortable (same as standing quietly)				Moderately Uncomfortable					Very Uncomfortable
1	2	3	4	5	6	7	8	9	10

4. Please explain any problems you may have encountered due to this harness (comfort, design, fit, etc.):

5. What other observations did you have about using this fall arrest harness?

6. What suggestions do you have for improving the design of this fall arrest harness?