Abstract

Southard, Stephanie Ann. Evaluating a New Design for the NASA SCAPE Harness (Under the direction of Dr. Gary A. Mirka)

The National Aeronautical Space Administration (NASA) uses a backpack system as a form of load carriage in the Self Contained Atmospheric Protective Ensemble (SCAPE) suits. SCAPE suits, which are completely enclosed suits, are required in areas where fuel and an oxidizer are present and can spontaneously ignite on contact (hypergolic atmospheres). Inside the SCAPE suit, a person wears a "backpack", which consists of a 40 pound environmental control unit (ECU) attached to a "backpack" harness. Interviews was conducted with current and former SCAPE employees to identify the body positions assumed while performing common tasks during a SCAPE operation, and to explore issues of discomfort while wearing the harness. The purpose of this research has been to develop and evaluate a new harness by comparing it with the current NASA harness in terms of biomechanical loading and subjective assessment.

A Kelty® Sierra Crest M'S external framed pack was chosen as the harness to modify, because it featured many components that are important to a supportive pack, including an external frame, a padded hip belt, load lifter straps, padded shoulder straps, and an adjustable harness for varied torso lengths. In addition to this basic design, lateral stiffness rods were added to the harness to help transfer the load from the shoulders to the hips.

To test the biomechanical effects of the NASA harness and the new harness on the body, the muscle activity of the trapezius, erector spinae, and rectus abdominus muscles were recorded using surface electromyography (EMG). While wearing each harness, subjects were required to position their torso in four different forward flexion

angles, 15, 30, 45, and 60 degrees, while EMG was recorded. The subjects were also asked to fill out subjective surveys based on the comfort level of the shoulders and low back for each harness.

The results for the trapezius muscles showed that there was a significant effect of the interaction of harness type and forward flexion angle on these muscles. The normalized EMG for the trapezius muscles showed there was a 14% and 11% reduction in muscle activity at 15 and 30 degrees, respectively, with the new harness compared to the NASA harness. The results for the erector spinae muscles showed that there was a significant effect of forward flexion angle and the interaction of harness type and forward flexion angle on the these muscles. The normalized EMG for the erector spinae muscles showed there was a 24% and 14% reduction in muscle activity at 15 and 30 degrees, respectively, with the new harness compared to the NASA harness. The rectus adominus muscles did have a significant effect of forward flexion angle, although there was not a distinguishable difference in muscle activity between the new harness and the NASA harness.

The subjective surveys agreed with the EMG results, which showed the new harness was more comfortable with respect to the shoulder and low back areas, as well as overall comfort than the NASA harness. Using a five point Likert scale, (where 1 meant no discomfort, 3 meant moderate discomfort, and 5 meant very uncomfortable) the evaluation of pressure on the shoulders from the shoulder straps showed that the NASA harness scored a 2.6, while the new harness had a score of 1.8. For discomfort felt in the trapezius muscles, the NASA harness scored a 3.1, while the new harness scored a 1.9. For the discomfort felt in the low back area, the NASA harness scored a 2.8, while the new harness scored a 1.9. As far as overall comfort for each harness, the NASA harness scored a 3.1, while the new harness scored a 2.1. Each question also proved to be statistically different between harness type. Collectively, the subjective and objective results show a significant improvement with the new harness system.

Evaluating a New Design for the NASA SCAPE Harness

By

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A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirement for the Degree of Master of Science.

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Biography

Stephanie Ann Southard was born on June 7, 1981 in Melbourne, Florida. She is the older sister of Jennifer Dianne Southard. Her mother, Patricia Southard, raised both Stephanie and Jennifer by herself, and has done an absolutely, wonderful job! Patty is currently a manager of the software engineering program at International Telephone and Telegraph (ITT) at Patrick Air Force Base, FL where she is responsible for the sustainment of the software systems at the Eastern Range. Jennifer will be graduating in May 2005 with a B.S. in Exercise Physiology from Florida State University, and will then head to medical school to become a Doctor in Osteopathy.

In May of 1999, Stephanie graduated high school from Melbourne Central Catholic in Melbourne, Fl, and decided to go to North Carolina State University on a full gymnastics scholarship and to pursue a degree in biomedical engineering. In four years, she graduated with a B.S. in Biomedical Engineering and Biological Engineering. It was here that she also met her best friend and the love of her life, Kevin Monk. During this time, she also summer interned with Lockheed Martin Mission Systems at Cape Canaveral Air Force Station in Cape Canaveral, FL. It was during her last year as a summer intern with Lockheed Martin, when her mom told her about the exciting field of human factors and ergonomics. After talking to Dr. Gary Mirka about the possibilities in this field, Stephanie decided to obtain her M.S. in Industrial Engineering at North Carolina State University. While working towards her master's degree, Stephanie had the honor of working for Dr. Gary Mirka as a Graduate Research Assistant. Stephanie looks forward to graduating in May 2005 and starting her first job as an Automation Engineer at Diosynth Biotechnologies in RTP, NC.

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1 Introduction

Throughout history, various load carrying devices have been devised to efficiently and safely move loads from place to place. The most common forms of manual load carriage are the backpack, including external and internal framed backpacks, doublepack (front and back pack), and rucksacks. Some areas that still use the basic form of manual load carriage include the military, emergency personnel, and recreational activities.

Load carriages, including backpacks, have been linked to back pain and low back problems. In fact, back problems associated with a load carriage system have shown to account for up to 22% of all load carriage injuries (Knapik et al., 1992). Since back pain is currently the second most frequent complaint of people who visit the doctor (Guyer, 2001) with approximately thirty-one million Americans experiencing low back pain at any given time (Jenson et al., 1994), and as many as 80% of all people will experience back pain at some point in their life time (Valfours, 1985), it is important to determine potential risk factors for low back problems in various work and recreational activities.

Since backpacks are a common form of load carriage, many researchers have studied the effects of these external loads on back and spine biomechanics. Most of the research has been focused on military personnel (Knapik 2004; LaFiandra et al., 2004; Quesada et al., 2000) and children (Steele et al., 2003; Pascoe et al., 1997), while others have been generalized to recreational activities such as hiking (Bloom & Woodhull-McNeal., 1987; Stuempfle et al., 2004).

1.1 Spine Loading and Backpacks

To examine the effect of an external load on the spine, biomechanical models are often used to predict the forces and moments experienced by the spine. These forces and moments are directly influenced by the posture and the magnitude of the external load. When a load is applied to the back, as in the case of a backpack, the center of gravity shifts posteriorly (Goh et al., 1998), causing the body to tilt slightly backwards. To counteract this off-balanced body position, a person tends to have a forward flexion of the torso to maintain the body's and backpack's center of mass over the feet (Bloom & Woodhull-McNeal., 1987; Knapik et al., 1996; Vacheron et al., 1999), which shifts the center of gravity anteriorly (Goh et al., 1998) and creates a sense of balance and stability.

Since the body manages an external backpack load through a forward flexion of the torso, there is an increase in the internal forces and moments about the lumbosacral (L5/S1) joint. The two main forces on the spine are the compressive and shear forces. Increases in the compressive forces are due to the weight of the external load placed on the back and the increase in the muscle forces used to support the external load on the torso. Increases in shear forces are a result of the external load and the forward flexion of the torso. The mass moment of inertia also increases about the L5/S1 joint, creating additional challenges during dynamic activities.

1.2 Basic Load Carriage Designs

Research has been done on the different forms of load carriage and different types of backpack design (e.g. Bloom & Woodhull-McNeal., 1987; Datta & Ramanathan, 1971; Holewign, 1992; Kirk & Schneider, 1992; Knapik et al., 1996; Knapik et al., 2004; LaFiandra et al., 2004; Lloyd & Cooke, 2000; Reid et al., 2004). Datta & Ramanathan (1971) made comparison of seven modes of load carriage, which included using the head, a rucksack (which is a pack that is strapped around the shoulder as a high pack), a double pack (which is when the load is equally divided in two packs, one across the front and the other on the back), a rice bag (which is when the load is in a gunny sack and supported on the back with the hands holding the upper two corners of the sack), a sherpa (which is similar to a rice bag, but the bag is supported by a strap around the forehead), a yoke (which is when the load is divided equally and is suspended by three ropes at each end of a resilient bamboo strip placed across the shoulder and is held with one or both hands for balance), and the hands. Subjects carried a 30 kg load of granite chips in each method of load carriage for 1 km at a speed of 5 km/hr while their oxygen consumption, pulse rate, and minute ventilation were recorded during the entire load carrying task and during a 5 minute recovery period afterwards. The results showed there was a significant difference ($p<0.01$) in the three physiological parameters due to a difference in the method of load carriage. The double pack proved to be the most physiologically efficient mode for carrying loads, while also ensuring a greater sense of stability, followed closely by the head mode. Using the hands as a form of load carriage proved to be the worst method of load carriage both ergonomically and as far as the three physiological parameters were concerned.

Other researchers have specifically compared backpacks to double packs, since these two methods have been associated with lower energy costs and are a more practical method for military operations (Knapik et al., 2004; Lloyd & Cooke, 2000). The double pack was found to be the most efficient and an ergonomically correct form of load carriage, because it promotes anterior-posterior stability by distributing half of the load in the front and half the load in the back (Datta & Ramanathan, 1971; Lloyd & Cooke, 2000). However, the double pack has shown to be less comfortable and cannot be donned on or off easily. The double pack also inhibits movement of certain tasks and limits the field of vision since half of the pack is positioned in the front of the body (Knapik et al., 2004). The backpack, on the other hand, provided the most versatility and ease of use while performing certain tasks since the load is just positioned on the back (Knapik et al., 2004).

There are several backpack design features that have contributed to comfort, quality, and improved overall function. These features include frame design, the addition of a hip belt, and the addition of lateral stiffness rods. These features all play a role in reducing the amount of force and pressure exerted on the back and shoulders by the backpack.

The two most common forms of framed backpacks are the internal frame pack and the external frame pack. Internal frame packs have two metal supporting structures sewn into the back panel of the pack which allows the pack to be closer to the center of mass of the body, lowers the center of mass, and allows the load to ride directly on a person back, creating a better sense of stability and control, but reduces back ventilation (Knapik et al., 2004). External frame packs have one metal frame outside the material of the pack, which places the pack further away from the center of mass of the body, creates a higher center of volume, and keeps the pack off the body for better body ventilation (Knapik et al., 2004).

Bloom & Woodhull-McNeal (1987) evaluated an internal frame pack and an external frame pack by examining the postural adjustments associated with each pack compared to a typical standing posture (the control position). The male subjects had a load of 19 kg in their packs and the female subjects had a load of 14 kg in their packs. The subjects stood profile to a reaction board while positions of their knee, hip, shoulder, and ear were photographed. Although both packs caused the subjects to lean forward, the subjects' knee, hip, shoulder, and ear reference points all proved to be significantly ($p<0.02$) further forward for the internal frame pack than the external frame pack. The greater increase in forward flexion with the internal frame pack is due to the fact that this pack creates a greater displacement and torque about the hips since the center of mass is lower, creating a greater sense of stability and balance. As far as subjective preference of a framed backpack, gender has proved to be a factor. Bloom & Woodhull-McNeal (1987) determined that the changes in male and female positions did not differ in respect to the different body parts examined while wearing either pack. However, Bloom & Woodhull-McNeal (1987) noted that the females overwhelmingly preferred the external-frame pack while the males overwhelmingly preferred the internal-frame pack.

Another study (Kirk & Schneider, 1992), examined the physiological (oxygen consumption, heart rate, respiratory exchange ratio, and minute ventilation) and perceptual responses of the internal and external frame packs on females. The results showed there was no difference in physiological or perceptual responses in females when carrying either type of framed pack. This indicates that choice of pack may be tied to general comfort of that pack rather than the specific type of frame in the backpack.

The hip belt is another design feature that helps improve the performance of certain upper body tasks during load carriage (LaFiandra et al., 2004; Knapik et al., 1996; Holewign, 1992) and has actually become a standard feature of most backpacks. One problem associated with backpacks is the pressure exerted on the shoulders by the straps from the backpack itself. The pressure on the shoulders using a frameless pack with only a 10 kg load was shown to be 200 mmHg (Holewijn, 1990). Using a framed pack with a hip belt actually reduced the amount of pressure on the shoulders by displacing the major mass of the load from the shoulders to the hips. The hips are considered to have a higher pressure tolerance than the shoulders (Holewijn, 1990), so transferring the load to the hips with a hip belt decreases the overall discomfort. The hip belt also centralizes the load on the waist, localizing the discomfort on the mid-trunk and upper legs instead of the neck and shoulder areas (Holewign & Lotens, 1992). Using a hip belt to transfer the load to the hips brings the load closer to the body center of mass, which goes along with Leggs' (1985) recommended guidelines for backpacks. Research has also shown that the use of a hip belt with a framed backpack transfers approximately 30% of the vertical force of the backpack to the hips (LaFiandra et al., 2004; LaFiandra & Harman, 2003).

Along with a hip belt, Reid et al., (2004) have suggested adding lateral stiffness rods to the lateral edges of the suspension system of the backpack. A stiffer suspension system improves load control, because the system moves in response to an individual's torso motion, which transfers more of the vertical load to the hips (Stevenson et al., 2004b). These lateral stiffness rods have shown to transfer 14% of the vertical load from the upper back and shoulders to the hips, decreasing the amount of vertical force applied to the torso without increasing the shear force. The lateral stiffness rods also created a 12% increase in the extensor moment about the medio-lateral axis at L3-L4 (Reid et al., 2004). This increase in the extensor moment reduces the likelihood of forward flexion of the torso, allowing an individual to stand more upright, which decreases the amount of muscle activity of the erector spinae muscles, and may delay the onset of muscular fatigue in the back (Stevenson et al., 2004b).

1.3 Biomechanical Studies of Backpacks

Stress during load carriage can be evaluated by electromyography (EMG) and a biomechanical analysis of the forces and moments on the spine. Although forces and moments cannot be measured directly without invasive measures, these variables are important to determine safety and the risk of injury. A biomechanical model can also help evaluate the mechanical stresses on the body from load carriage that can lead to back problems.

EMG analysis can be useful in determining the amount of muscle activity (stress) in the musculoskeletal system during a load carrying task. EMG analysis has been used to look at the differences between relatively light loads (less than 20 kg) and heavier loads (greater than 30 – 40 kg) in backpacks. Research has shown that there is actually a decrease in EMG activity in the erector spinae muscles during light load carriage than with no load (Bobet & Norman, 1984). The reason for this decrease in erector spinae muscle activity is that a person's posture, when a small load is added, actually causes the center of mass of both the backpack and the body to be positioned further back than the center of mass of the body alone, which creates less tension on the erector spinae muscles than if there was no load on the body. Heavier loads, however, do result in more erector spinae muscle activity than with no load. (Knapik et al., 1996)

EMG analysis has also been used to evaluate the effects of load placement in the backpack. Bobet & Norman (1984) measured the EMG activity on the trapezius muscles and the erector spinae muscles around L4. A 19.5 kg load was placed at the C1-C7 region and the T1-T6 region. For static situations, there were similar moments for both the high and low load placements. As for dynamic situations, the C1-C7 region created a significant increase in the levels of muscle activity of both the trapezius and erector spinae muscles compared to the T1-T6 region. Also, placing the load at the C1-C7 region compared to the T1-T6 region created a moment about L5/S1 that was approximately 40% greater, which is attributed to the greater rotational inertia of the higher load placement. As a result, higher load placements can cause relatively high muscle forces to maintain postural stability. Therefore, positioning the load around the T1-T6 region places the load's center of mass as close to the body as possible, creating a more efficient mode for load carriage.

Cook & Neumann (1987) evaluated the lumbar paraspinal EMG activity during the stance phase of walking with no load, 10% of the subject's body weight, and 20% of the subject's body weight, while carrying a load in four different positions. In the first two positions, the load was held in the hand (similar to carrying a suitcase) and positioned either contralateral or ipsilateral to the electrode site (the electrode was either placed on the right or left paraspinal muscles). For the third position, the load was carried anterior to the chest with both hands. For the fourth position, the load was carried on the back (posterior) using padded straps provided by a backpack. The EMG results showed that the posterior position required the least amount of muscular effort, while the anterior carrying position required the highest amount of muscular effort. The results also showed that there was actually a decrease in the EMG activity of the lumbar paraspinal muscles when the load carried on the back was below 20% of the individual's body weight (Cook and Neuman, 1987). These results can be compared with Bobet and Norman's (1984) findings which are stated above.

Gait analysis has also been researched to see how the body changes and attempts to maintain balance and stability during walking. When a load is placed on the human body, adjustments must be made so an individual does not get injured or fall. Adjustments in gait, including walking speed, stride length, and stride frequency are due in part to the increase in muscular forces and moments from load capacity, load placement, curvature of the spine, and postural adjustments (LaFiandra & Harman 2003; Kinoshita, 1985; Orloff & Rapp, 2004). LaFiandra & Harman (2003) looked at the distribution of forces between the upper and lower back during load carriage. They had male subjects carry three different load masses (13.6 kg, 27.2 kg, and 40.8 kg) while walking on a treadmill at a speed of 1.34 m/s. Force transducers were attached to the hip belt to measure the amount of force that was applied to the lower back. The amount of force applied to the upper back was determined by calculating the total force between the subject and the backpack and subtracting that from the force applied to the lower back. Their results showed there was no correlation between backpack mass and the distribution of weight that the upper and lower back supported. The upper back supported approximately 70% of the load of the pack, while the lower back supported the remaining 30% of the load, regardless of load magnitude. Increasing the load of the backpack did create an increase in the peak and mean vertical and anterior/posterior forces on the lower back and upper back proportionally. The vertical force of the center of mass of the backpack increased proportionately more than the weight of the backpack, since there was a greater moment of the center of mass of the backpack about the lumbosacral joint when the load was increased. It should be noted, though, that information is still lacking on what the optimal percentage of load distribution should be to reduce the potential for low back pain from the forces applied to the back.

Carrying loads with a backpack can also impact the curvature of the spine and the actual curvature of the spine alone has consequences for back problems. Orloff & Rapp (2004) completed a study on the effects of load carriage on spine curvature as the body fatigues. Subjects walked on an indoor track for 21 minutes, while data was collected using a data recorder backpack with variable resistance connected to the rods protruding out of the backpack. Data was taken at two time periods: at 3 minutes (rested condition) and 18 minutes (mildly fatigued condition). Orloff & Rapp (2004) found that there was a significant increase in the curvature of the spine from the thoracic region to the lumbar region of the back as a function of fatigue. This increase in spine curvature could result in an increase in the moments about L5/S1, causing an increase in the compressive and shear forces on the intervertebral discs.

To determine how the compressive and shear forces of the lumbosacral spine are affected by varying the loads during walking, Goh et al. (1998) conducted a study to compare various loads in a backpack to the forces created on the spine from those loads during walking. Ten male subjects walked on level walkway with three different loading conditions: no load, with 15% of their body weight, and 30% of their body weight. A 5-camera Vicon motion analysis system (Oxford Metrics Limited, Botley, Oxford, UK) was used to examine kinematic data on stride characteristics (stride length, stride frequency, and walking speed). Two Kistler force plates (Kistler Instrumentee AG, Winterhur, Switzerland) were also placed in the middle of the walkway and were used to determine the ground reaction forces. A biomechanical model was developed to determine the changes in the peak forces about the lumbosacral joint for the varying loading conditions. The results showed that all ten subjects had an increase in forward flexion posture as the load increased, and the backpack loads of 15% and 30% created disproportionate increases in the lumbosacral joint by 26.7% and 64%, respectively. Breaking down the lumbosacral forces into a compression force and a shear force exerted on the lumbosacral joint, the magnitude of the shear force was much lower than the magnitude of the compression force. The constant ratio of shear to compressive force was found to be 0.18 for the two different loading conditions. The results also showed that there was no significant difference in stride length, walking speed, or cadence when there was an increase of the load in the backpack. However, Goh et al. (1998) states that the subjects selected for the experiment were seasoned users of backpacks, so stride characteristics were not significantly affected. Furthermore, Kinoshita (1985) hypothesized that to produce an effect on basic gait parameters, sedentary workers would be more sensitive to load carriage compared to those that frequently or familiar with carrying loads.

Despite the results from Goh et al. (1998) on basic gait parameters, most research suggests that increasing the load in a backpack will result in a decrease in walking speed, a decrease in the amount of time an individual is in the single stance (support) phase, and an increase in the amount of time an individual is in the dual stance (support) phase (Knapik et al., 1996; Martin & Nelson, 1986; Kinoshita, 1985; Lloyd & Cooke, 2000; Quesada et al., 2002; Wang et al., 2001). These changes in gait allow the body to adjust to the load carriage and enhance the stability and balance of the load on the body while walking. The impact of the mechanical stress on the body per stride while walking increased in the dual support phase and decreased in the single support phase (Wang et al., 2001). The increase of stress in the double support phase was a result of the distribution of the load over both legs, while a decrease in the stress in the single support phase was a result of the faster transfer of body weight over one leg due to the faster stride frequency. To decrease the amount of time in the double support phase, Kinoshita (1985) suggests that shortening the length of the stride and increasing the stride frequency would reduce the mechanical stresses on the body, since there would be less time in the push-off phase of walking. However, Martin & Nelson (1986) found that a shorter stride length and an increase in stride frequency actually increased the mechanical stresses on the body, because a greater number of steps induces repeated mechanical stresses on the body.

Differences in gait between men and women were also analyzed as the load increases in a backpack. Martin & Nelson (1986) specifically looked at the differences in walking patterns in men and women as the load in the backpack increased. Eleven males and eleven females carried a backpack with weights of 0, 9, 17, 29, and 36 kg. The subjects walked at 1.78 m/s with the five different loading conditions while being filmed with high speed cameras. The variables analyzed in this experiment were stride length, stride frequency, single stance time, and dual stance time. The results showed that there were considerable differences in the gait patterns between the men and women for all loading conditions. The women were more sensitive to an increase in load carriage than men. The men had relatively smaller changes in gait patterns compared to the women's changes, although both the men and women showed a decrease in stride length, an increase in the double support time, and an increase in forward flexion. The women did have a larger decrease in stride lengths, a greater stride frequency, a decrease in single leg support time, and a greater increase in forward flexion compared to men. Therefore, as the load increases in a backpack, a woman's gait pattern and postural adjustment is affected more then men. These results agree with the other researchers who have also examined the effects of gait characteristics in response to increases of loads in a backpack between men and women (Knapik et al., 1996; Kinoshita, 1985; Lloyd & Cooke, 2000; Martin & Nelson, 1986; Wang et al., 2001).

1.4 Basic Backpack Design Considerations

Since backpacks are a popular method of load carriage, a considerable amount of research has been devoted to determining their optimal design, including load capacity, load placement, and load distribution that will decrease the amount of stress placed on the body (Bobet & Neuman, 1984; Datta & Ramanathan, 1971; Haisman, 1988; Kirk & Schneider, 1992; Leggs, 1985; Lloyd & Cooke, 2000).

Load capacity is an important variable in a backpack, since load has a direct effect on the amount of stress placed on the back. It is almost impossible to classify a maximum load in a backpack, since age, gender, muscle strength, body composition, and anthropometry are all physical factors that play a role in the amount of weight a person should carry. Even though a maximum load is hard to define, the traditional consensus for the optimal load has been calculated to be one-third the body weight of the individual (Haisman, 1988) or 25-30% of the individual body weight (Leggs, 1985). It is important to know the optimal load of a backpack, since task performance can be affected by the load in the backpack.

Aside from backpack design and load capacity, the placement and distribution of the load can also play a role in decreasing the amount of stress on the back. Leggs (1985) developed a set of guidelines for load carriage that, in principle, should place the load's center of gravity as close to the body as possible, which promote stability, and makes use of the larger muscle groups in the body. The common practice for load placement is to put lighter items at the bottom of the pack while placing heavier items at the top of the pack (Howe & Getchell, 1995). Placing loads high in the pack focuses the load over the body's center of gravity, which is in agreement with Leggs' recommendations (1985).

When carrying a load on the back, adjustments must be made by the body's posture in order to maintain stability and balance. As stated before, the body automatically tends to have a forward flexion of the trunk when a load is applied to counterbalance the body's and backpack's center of mass over the feet (Bloom & Woodhull-McNeal., 1987; Knapik et al., 1996; Vacheron et al., 1999). The body tends to lean forward more when the load is placed low in the pack than if it was placed high in the pack. If the load is placed low in the pack, the body tends to lean so the center of mass is over the front half of the foot. Heavy loads placed high in the pack are preferable for even terrain since the body is able to maintain a more stable and upright body posture (Knapik et al., 1996).

Physiological and perceptual responses were also found to be affected by load placement. Stuempfle et al. (2004) examined how changing the load distribution in an internal frame pack will affect these physiological and perceptual responses on the body. Ten female subjects carried 25% of their body weight in the pack and walked on a level treadmill for 10 minutes while the load was placed in three different positions: high – T1-T6 (same position used in Bobet & Norman, (1984)); central – T7-T12; and low – L1-L5. The subject's heart rate, minute ventilation, oxygen consumption, respiratory exchange ratio, respiratory rate, and ratings of perceived exertion were all measured during the experiment. The high load placement was shown to be the most efficient and desirable method of load carriage over low load placement. Oxygen consumption, minute ventilation, and the rating of perceived exertion were all significantly lower when the load was placed in the high position as compared to the low position ($p=0.002$, $p=0.02$, $p=0.03$, respectively). Therefore, placing loads high in the backpack may improve the performance of an individual performing certain tasks.

As of now, all research on load carriage assessment has been based on human participants used in experiments. Since there was not a physical or mathematical human model that standardized an efficient biomechanical method for load carriage, Stevenson et al. (2004a) developed some biomechanical assessment tools for analyzing human load carriage. A list of performance criteria and load carriage design principles have been created from these assessment tools that can be used to develop and design load carriage systems for humans for military, industrial, and recreational uses.

Stevenson et al.'s (2004a) set of performance specifications were based on previous literature and research. Most of these specifications were configured based on soldiers' reports on discomfort and actual pressures and forces that were calculated from a static biomechanical model. These specifications state that: 1) relative motion between pack and person to be less than 14 mm; 2) Mean skin contact pressure to be less than 20 kPa; 3) Maximum continuous skin point pressure to be less than 45 kPa; 4) Forces borne by both shoulders to be less than 290 N; and 5) Lumbar shear contact force to be less than 135 N. The mean skin contact pressure was based upon military personnel that reported discomfort at 20 kPa for 95% of the soldiers, while the maximum point pressure measurement was based on the fact that blood can occlude at 14 kPa. The lumbar shear contact force was based upon a correlation of r = 0.93 between subjective discomfort and lumbar reaction force.

To design and configure a load carriage system, certain design criteria should be establish as to create a backpack that reduces the forces and moments on the back. According to Stevenson et al. 2004a, a backpack should:

- Transfer the load off the shoulders to the hips via a hip belt
- Use lateral stiffness rods, when applicable, to help transfer the load to the hips
- Place the load's center of gravity as close to the body as possible
- Position the load around the T1-TC region
- Utilize the larger muscle groups in the body
- Minimize the pressure exerted on the shoulders by the straps
- Ensure stability
- Ensure the lowest metabolic costs

1.5 The NASA SCAPE suit

The National Aeronautical Space Administration (NASA) uses a backpack system as form of load carriage in the Self Contained Atmospheric Protective Ensemble (SCAPE) suits. SCAPE suits are required in areas where fuel and an oxidizer are present and can spontaneously ignite on contact (hypergolic atmospheres). The space shuttle program at Kennedy Space Center and the 45th Space Wing of the United States Air Force at Cape Canaveral Air Force Station in Cape Canaveral, Florida require service and maintenance of launch activities in these hypergolic atmospheres to prepare and support shuttle and rocket launches.

The SCAPE suit is a completely enclosed suit, which is required by the Occupational Health and Safety Administration (OSHA) since they label hypergolic atmospheres as areas that are immediately dangerous to life and health. Inside the SCAPE suit, a person wears a backpack system, which consists of cryogenic liquid air in an environmental control unit (ECU). The dimensions of the ECU are 22.5 inches high, 18 inches wide, and 9 inches deep and weighs approximately 40 pounds. The cryogenic liquid air exits the ECU by traveling through tubing to a flow control valve and is released throughout the suit by the air distribution system of the suit. This system allows a person to breathe regularly, without the use of a regulator or respiratory device.

Once a person suits up for a SCAPE operation, they are in the suit for a maximum of two hours per SCAPE operation, and will break for approximately two hours. This sequence can be repeated two to three times during a 10-12 hours shift. During a SCAPE operation, the main responsibilities of a SCAPE employee is to either fuel the rockets, clean up hazardous chemical spills or leaks, remove hazardous gases, connect thrusters for the auxiliary power units (APUs), or load propellants (such as MMH and N_2O_4). These tasks require a lot of walking, going up and down stairs, and getting on their hands and knees to complete a task. These maneuvers require the body to be in non-neural postures, which increases the muscle activity of the erector spinae muscles. Other tasks require a SCAPE employee to do work with their arms above their head, which increases the muscle activity of the trapezius muscles. After one shift, a SCAPE employee usually experiences fatigue as if "you have just done a tiring workout" (comment from interviewing one of the SCAPE employees).

Interviews were conducted with five different current and past SCAPE employees at Kennedy Space Center, Florida on October 7-8, 2004. The employees described typical tasks performed while in the SCAPE suit, and areas of discomfort felt from the SCAPE harness while performing these tasks. The employees said they positioned their bodies in several different angles and positions, depending on the type of task that had to be performed and the type of environment they were in. The employees said they would lean on rails with their arms extended, get on their hands and knees, and also get completely flat on their stomachs on the ground while performing particular tasks. When asked how they spent most of their work time, the respondents said they spent the majority of their time walking on different types of surfaces, leveled and unleveled, and also going up and down stairs. All of the employees said their biggest complaint was the discomfort or pressure felt in the shoulder region caused from the shoulder straps of the current NASA harness. Some of the employees said they could feel a little stress placed on their low backs while wearing the ECU, although it wasn't a major area of discomfort for them.

To determine the body positions of the torso, including non-neutral postures, of the

SCAPE employees performing certain tasks, a video was analyzed which showed SCAPE employees performing several common tasks that require them to position their bodies in a variety of positions while in a SCAPE suit. The video showed that while the SCAPE employee was walking, there was a slight forward lean of the torso to support the ECU, which was estimated to be around a 15 degree forward flexion angle. The video also showed the employee leaning over between a 30 and 45 degree angle while standing up performing specific tasks. The last task shown on the video was the employee on their knees, with their torso leaning over performing a particular task.

In an effort to improve the SCAPE working environment and keep employees risk free of injuries, NASA is examining the current SCAPE suit design. Part of this improvement is to design a new harness to reduce biomechanical stresses on the body. The current NASA harness does not have a supportive hip belt (it just has a strap that goes around the hips), so most of the load is felt on the shoulders and the low back, and has very thin shoulder straps, which is increasing the pressure on the shoulders. Any new harness should include a supportive and padded hip belt, padded shoulder straps, and lateral stiffness rods (Stevenson et al., 2004a).

The scientific motivation of this study is to examine the effects of a backpack harness system on the trapezius, erector spinae, and rectus abdominus muscles, while positioning the torso in several different forward flexion angles. Currently, there is a void in the scientific literature on the effects of these muscles while carrying a load on the back in non-neutral postures. Since common tasks in a SCAPE operation require a SCAPE employee to position themselves in non-neutral postures, further analysis must be conducted to evaluate the amount of stress placed on the body while supporting the ECU on the back via a harness system in these non-neutral postures.

1.6 Objective

The objective of this study is to develop and evaluate the effects of a newly designed harness in terms of biomechanical loading and subjective assessment by the user. It is hypothesized that a new harness (that incorporate a hip belt and lateral stiffness rods) will reduce the activity of the erector spinae, rectus abdominus, and trapezius muscles. It is also hypothesized that the new harness will improve the comfort level, particularly in the shoulder region, since the pressure in the shoulder region is the primary complaint by most SCAPE employees, and in the low back, since the load will be more focused on the hips due to the addition of a hip belt and lateral stiffness rods.

2 Methods

2.1 Subjects

The participants in this experiment were twelve males and three females ranging in age from 21 to 55 years old. The subjects were recruited through word of mouth around the Raleigh, NC area. Each subject provided a written informed consent (IRB approved) prior to participation in the experiment (Form shown in Appendix A). Table 1 shows the means and standard deviations of relevant anthropometric characteristics such as: stature, mass, chest circumference, waist circumference, shoulder height (acromion to ground), and waist height (top of iliac crest to ground).

Table 1: Subject anthropometry

	Mean	Std. Dev.	Min.	Max.
Height (cm)	170.6	28.6	72	199.5
Weight (kg)	87.1	20.9	59.42	127.0
Shoulder Height (cm)	149.4	8.3	138	170.1
Waist Height (cm)	107.3	5.9	99.7	121.0
Chest Circumference (cm)	103.0	11.4	90.2	121.9
Waist circumference (cm)	90.9	14.7	71.1	119.4

2.2 Testing Apparatus

2.2.1 The Mock-up Environmental Control Unit (ECU)

A mock-up ECU was built out of ½ inch plywood, stuffed with newspaper, and fiber-glassed to simulate the real size and weight of NASA's SCAPE ECU. The simulated ECU has the same dimensions of NASA's SCAPE ECU: 22.5 in. high x 18 in. wide x 9 in. thick and a uniformly distributed weight of 40 pounds (Figure 1).

Figure 1: The mock-up ECU

2.2.2 The Current NASA SCAPE Harness

The current NASA SCAPE harness was developed in the 1970s and is still in use today (Figure 2 and Figure 3). Examining this harness, most of the load is placed on the shoulders. This corresponds to the main complaint of the SCAPE employees, in which they said they felt the most discomfort in the shoulder area while wearing the harness. Since there is no supportive hip belt in the harness system, most of the load is focused right on the shoulders.

Figure 2: The front view of the current NASA SCAPE harness

Figure 3: The side view of the current NASA SCAPE harness

The NASA harness is attached to the ECU with an upper mounting bracket and a lower mounting bracket (Figure 4).

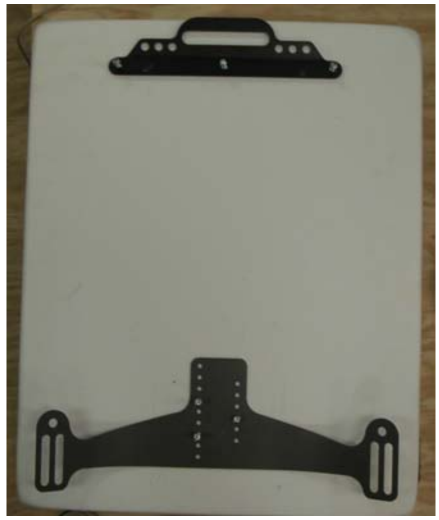

Figure 4: Upper and lower mounting brackets on the ECU

2.2.3 The New Harness

A Kelty® Sierra Crest M'S external framed pack was chosen as the harness to modify. This harness was chosen because it featured many components that are important to a supportive pack, including an external frame, a hip belt, load lifter straps, padded shoulder straps, and an adjustable harness for varied torso lengths. Lateral stiffness rods were added to the harness, to help transfer the load from the shoulders to the hips. All of these components are further discussed in detail below.

First, an external frame was chosen over an internal frame, because the external frame can act as a barrier between an individual and the ECU, therefore eliminating the "cold" feeling experienced by the SCAPE employee or the chance of ice forming on the posterior side of the SCAPE employee's pelvic area. Also, the external frame can be directly attached to the ECU without the use of the mounting brackets.

Second, the Kelty® harness has a supportive hip belt which is a standard component of almost all packs today (Figure 5). A hip belt is a very important feature of a harness, since most of the weight of the ECU should be concentrated on the hips to alleviate the amount of pressure on the shoulders. This hip belt is cushioned and has easy, adjustable straps so that the hip belt can be adjusted to a variety of different sizes, depending on an individual's waist size (minimum = 66 cm, maximum = 104 cm ; 3% female to 97% male (Gorden et al., 1989)). When a person wears the pack, the hip belt should be positioned so that the top 1/3 of the belt should be above the iliac crest (hip bone) and the bottom 2/3 of the belt should be below the iliac crest.

Figure 5: The hip belt of the new harness

Third, the Kelty® harness includes load lifter straps (Figure 6) and padded shoulder straps. The load lifter straps are attached to the shoulder straps and the top of the slider rail by means of a buckle and a slider attachment piece. The purpose of these straps is to help pull the ECU as close to the back as possible. The shoulder straps are sufficient padding and easy-to-reach adjustable straps which are located at the bottom of the shoulder straps. The shoulder straps and load lifter straps should be tightened so that the ECU is pulled as close to the back as possible to alleviate some of the pressure experienced by the low back. Positioning the ECU as close to the body as possible reduces the distance between the ECU and the back, and therefore decreases the moment about the spine at L5/S1.

Figure 6: Load lifter straps attached to the shoulder straps

Fourth, the Kelty® harness has a chest strap (Figure 7), so that the ECU will not move when the body moves and is positioned in non-neutral postures. The chest strap is also adjustable to accommodate varying chest sizes.

Figure 7: The chest strap of the new harness

Fifth, the Kelty® harness is adjustable based on the torso length (C7 to L5/S1). Figure 8 shows the smallest length of the harness (minimum torso length = 35 cm; 5% female (Gordon et al., 1989)). Figure 9 shows the largest length of the harness (maximum torso length = 50 cm; 90% male (Gordon et al., 1989)). The harness is adjusted by sliding the back portion of the harness up or down on the slider rails, depending on the length of an individual's torso.

Figure 8: The smallest length of the new harness

Figure 9: The largest length of the new harness

In addition to these basic features of the Kelty® harness, lateral stiffness rods (Figure 10) were added to this harness to help transfer the weight of the ECU from the shoulders to the hips. Two carbon fiber rods were used as the lateral stiffness rods. Two lateral compartments were created to house the rods. The top of the rods were inserted into the bottom of the upper horizontal bar. The bottom of the rods, which are enclosed in the compartment, are attached to straps which are located on each side of the hip belt. To use the rods, a person pulls the straps (that are attached to each side of the hip belt) tighter, which in turn pulls the rods forward. Since the tendency of the rods is to remain straight (not be in compression or tension), the rods force the ECU up and onto the hips. This mechanism allows more weight of the ECU to be transferred to the hips and reduces the amount of pressure felt on the shoulders and low back.

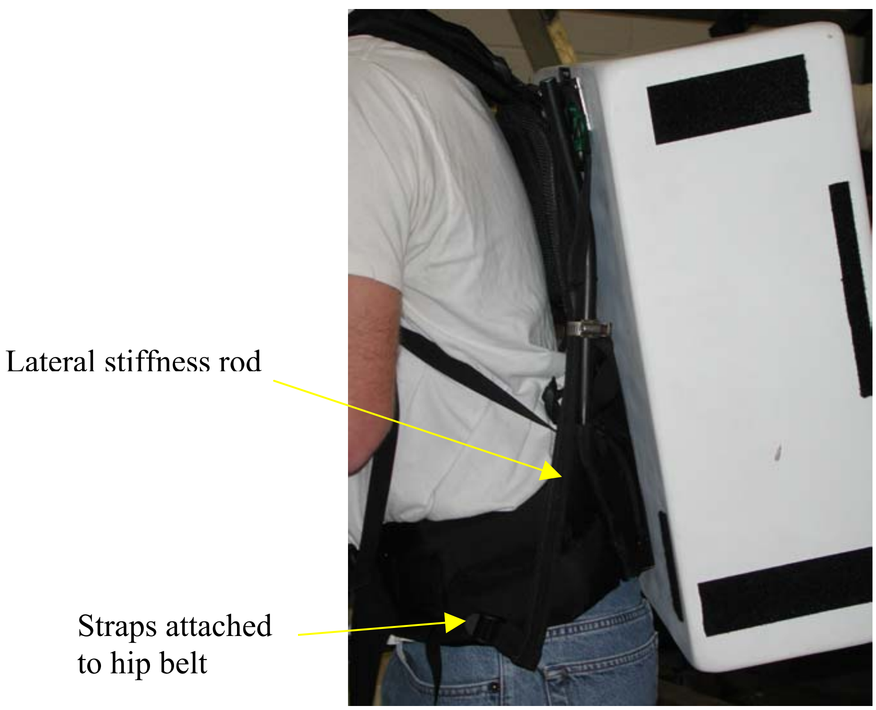

Figure 10: Lateral stiffness rods of the new harness

There was one design requirement that was dictated by the ECU: the new harness needed to have the same attachment points to the ECU as the current harness. To meet this requirement, the external frame had to be reduced in size to fit the attachment points of the ECU. The upper horizontal bar of the frame was cut and welded 20 inches from the bottom of the frame, thus shortening the overall size of the frame and making the upper horizontal bar of the frame the upper attachment point of the ECU. Since the upper horizontal bar is used to attach the harness to the ECU, there is no need for the upper mounting bracket that is used for the current harness.

One problem presented with the external frame is that it is curved to fit the body's natural curves, creating an uneven surface on which to mount the ECU. A lower mounting plate (Figure 11) was made to correct the uneven surface and to provide a method of attaching the new harness to the lower part of the ECU. An aluminum plate with dimensions of 10 11/16 in. high x 5 3/16 in. wide x 1/16 in. thick was used. The aluminum plate was bent 1 7/16 from the bottom at a 90 degree angle to create a level surface on which to mount the ECU. The top of the plate was welded on to the middle horizontal bar, but not to the bottom of the frame so that the hip belt compartment could be easily removed or put on the frame. Since the aluminum plate is used to attach the harness to the ECU, there is no need for the lower mounting bracket used in the original NASA harness. Special care was taken to ensure that the vertical position of the ECU relative to the C8 vertebrae of a person was the same for the new harness and the NASA harness. This was done to make sure the moment experienced by the erector spinae muscles due to the position of the ECU on the back was the same for both harnesses.

Figure 11: Aluminum plate attached to the frame of the new harness

The main goals of the new harness were to reduce the forces on the shoulders and low back, and to transfer the majority of the load from the shoulders and low back to the hips. With this redesigned harness, the shoulder straps should support a limited proportion of the ECU, as most of the load is placed on the hips. Figures 12 and 13 show the new harness with all of its modifications.

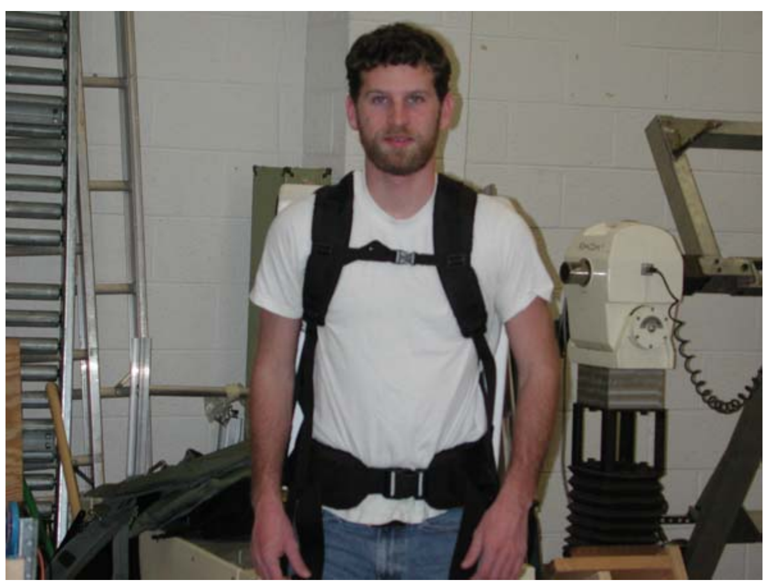

Figure 12: The front view of the new harness

Figure 13: The side view of the new harness

2.2.4 Experimental Equipment

Six pairs of bipolar surface Ag-AgCl electrodes (Model E22x, In-vivo Metric) were used to collect the EMG data from the right and left pairs of the erector spinae muscles, rectus abdominus muscles, and trapezius muscles. These data were pre-amplified (1000x) and then carried via shielded cable to the main amplifiers that filtered (60 Hz, and low pass 1000 Hz) and further amplified (50x) the EMG data. All EMG data was collected at 1024 Hz.

To provide the necessary static resistance for the collection of the angle-specific maximum voluntary contractions for the static extensions and flexions, a Kin/Com (Chatanooga Group, Inc., Hixson, TN), an isokinetic lumbar dynamometer, and a trunk motion reference frame were used. The dynamometer system was connected to the trunk motion reference frame to permit precise control of the angle-specific peak moment generated by the subject, and to capture the maximum voluntary contractions for the erector spinae and rectus abdominus muscles (Figure 14) (Mirka & Marras, 1993). A strap was wrapped around the trunk motion reference frame so the subject could pull on the frame to perform their maximum voluntary contraction for the rectus abdominus muscles.

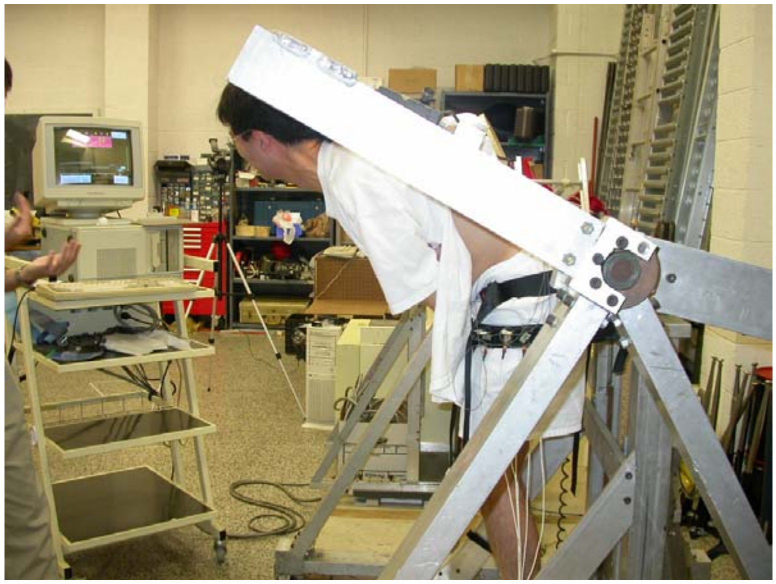

Figure 14: Dynamometer for the performance of maximum voluntary contractions for static extensions and flexions

To obtain the maximum voluntary contraction of the trapezius muscles, a handle was attached to a chain that was connected to a U-bolt in a piece of wood on the floor (Figure 15). To use this device, a person would stand on the piece of wood and hold the handle with their arms straight. Then, the person would shrug their shoulders and pull against the handle as hard as possible to obtain the maximum voluntary contraction.

Figure 15: The pull task for the trapezius muscles

2.3 Experimental Design

2.3.1 Independent Variables

There were two independent variables in this study. The first independent variable was harness type with two levels: the NASA harness and the new harness. The second independent variable was the forward flexion angle with four levels: 15, 30, 45, and 60 degrees. Each subject was exposed to all combination of harness and forward flexion angle. The entire design was replicated.

2.3.2 Dependent Variables

There were six dependent variables in this study. Three of the dependent variables were the averaged, normalized integrated EMG from the left and right sides of the erector spinae, rectus abdominus, and trapezius muscles. The left and right sides of each muscle were average together to get the muscle activity of each pair of muscles. These data represent the average of the normalized EMG of each pair of muscles during the three second, static hold of the angled posture.

The other three dependent variables were the results taken from the three discomfort surveys that were filled out by each subject. All surveys can be found in Appendix B. The subjects completed two post-test surveys, which were administered at the end of the experiment for each harness, and one comparison survey, which was administered after the subject had worn both harnesses and completed both experiments. The responses from the three surveys were to identify immediate/acute perceptions of discomfort while wearing each harness.

The two post-test surveys were titled “Subjective Survey – Green Harness” and “Subjective Survey – Black Harness.” The NASA harness was called the green harness and the new harness was called the black harness in the experiment so there would be no bias from the subject on which harness was NASA’s and what harness was the new harness. The surveys asked the same questions for each harness in the same order for all subjects. Subjects were asked to rate (on a five point Likert scale) the following four categories for each harness: the discomfort level felt on the skin of the shoulders, the trapezius muscles, the low back muscles, and the overall comfort of the harness. The five points on the scale ranged from 1 - no discomfort, up to 5 - very uncomfortable. For example, one statement read: “Please rate the discomfort level you felt on the low back while wearing the black harness.” The subjects were instructed to give their rating in response to the question by circling one of the five choices, based on their comfort level while performing the task wearing each harness.

The subjects were then asked to fill out a final comparison survey, entitled "Subjective Survey – Comparison of Harnesses", which queried the subjects on their preference of harness type. This survey, however, was constructed differently. The subjects were asked to compare the comfort level of the green harness to the black harness. The survey asked subjects to rate (on a five point Likert scale) the following three categories: overall comfort, comfort level while standing upright, and the comfort level while leaning forward in the 60 degree angle. The five points on the scale ranged from 1 - much worse, up to 5 - much better. For example, one statement read: "With regard to overall comfort, how would you rate the green harness to the black harness?" All data were collected and stored with a unique identifier number for each subject.

(Note: When discussing the surveys from this point on, the green harness is known as the NASA harness and the black harness is known as the new harness).

2.4 Experimental Procedure

Upon arrival, the subject was introduced to the procedures and the equipment used in the experiment. Six body measurements were then taken for the subject: height, weight, shoulder height, waist weight, chest circumference, and waist circumference. The subject then warmed-up their muscles, concentrating on the low back, trapezius muscles, and the hamstrings, by performing brief warm-up exercises.

After the subject felt their muscles were warmed-up, six pairs of bipolar surface electrodes were placed and secured over the right and left pairs of erector spinae (L2/L3 region), rectus abdominus muscles, and trapezius muscles to collect these muscle activity data (Figures 16-18). To obtain muscle activity data for the erector spinae muscles, surface electrodes were vertically placed approximately four centimeters from the midline of the spine at L2/L3 (Mirka & Marras, 1993), and the centers of the two electrodes were one inch apart. To obtain the optimal muscle activity data for the rectus abdominus muscles, surface electrodes were vertically placed approximately 1.5 inches lateral from the umbilicus (Mirka & Marras, 1993), and the centers of these two electrodes were also placed one inch apart. To obtain the optimal position for EMG amplitude of the trapezius muscles, Jensen et al., (1996) recommends placing the surface electrodes one centimeter lateral from the midpoint between the seventh cervical vertebra (C7) and the acromion process. However, this electrode placement is exactly where the shoulder straps are positioned; therefore, the electrode placements were moved two centimeters medial from the midpoint between C7 and the acromion process. These electrodes were placed horizontally on the trapezius muscles, and their centers were one inch apart from each other.

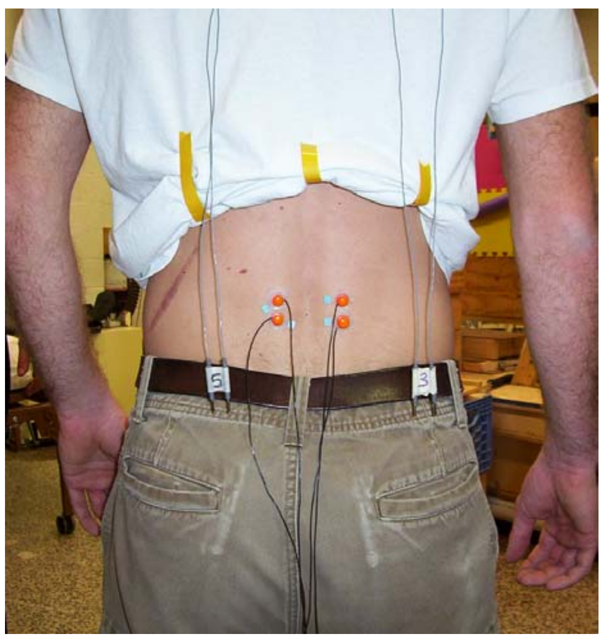

Figure 16: Location of electrodes for erector spinae muscles.

Figure 17: Location of electrodes for rectus abdominus muscles.

Figure 18: Location of electrodes for trapezius muscles

After the surface electrodes were positioned, the subject, securely fastened with a seat belt, stood with their backs against the trunk motion reference frame on the lumbar dynamometer apparatus. To perform a maximum voluntary contraction (MVC) for the erector spinae muscles, the subject pushed against the reference frame as hard as they could for five seconds while muscle activity data was collected for three seconds. To obtain the MVCs for the rectus abdominus muscles, the subject pulled against the reference frame, using a strap, for five seconds while muscle activity data was collected for three seconds. For both the MVCs for the erector spinae and rectus abdominus muscles, the reference frame was positioned at four different angles: 15, 30, 45, and 60 degrees from upright in the sagittal plane, and the subject was required to perform one MVC at each angle. The subject practiced using the dynamometer system to get comfortable with performing maximum extensions and flexions against the reference frame before their MVCs were actually recorded. The subject took a one minute break between consecutive MVCs. To obtain the MVCs for the trapezius muscles, the subject held onto a handle with both hands with straight arms, and shrugged their shoulders for five seconds while muscle activity data was collected for three seconds. The subject was required to perform two MVCs for the trapezius muscles.

Upon completion of the MVCs, the subject donned either the NASA harness or the new harness (defined by a randomization scheme: half started with the NASA harness and half started with the new harness) with the assistance of the researcher. The subject was then positioned in front of a chair and asked to position their torso in a one of four different forward flexion angles, 15, 30, 45, and 60, using a goniometer with a level that was attached to the ECU. Each subject was allowed a slight knee bend, since Shin et al. (2004) showed that knee angle had a significant effect on the erector spinae muscle activity. Each angle was performed twice for each harness, for a total of eight trials per harness.

Once the subject positioned their body in the specified angle (Figure 19), muscle activity data were collected for three seconds. After the data was collected, the subject took a one minute break before the next trial. Once the subject completed all the trials for one harness, the harness was removed, and the subject completed a post-test survey for that particular harness. There was a five minute break given to the subject before putting on the other harness. Once the other harness was placed on the subject, the experiment was repeated. After completing the experiment using the second harness, the subject completed the post-test survey for that particular harness and also completed the final comparison survey that compared the comfort level of NASA harness to the new harness. Finally, all electrodes were removed. The subject was thanked for participating in the experiment and given an NCSU Ergonomics t-shirt.

Figure 19: Subject leaning over at 45 degrees with the new harness

2.5 Data Processing

2.5.1 EMG Data

After the signal was filtered and amplified, the signal was rectified and averaged across the three second data collection period. This process occurred for both data collections for the MVCs and the experimental trials. The EMG data collected during the

MVCs were partitioned into 1/8 second windows for the three second interval and the maximum of the 24 windows for each muscle in each posture were identified and used as the denominator in the process to normalize the EMG.

2.5.2 Survey Data

The survey data, consisting of the three subjective surveys, were compiled in a spreadsheet. The responses for the post-test survey were separated by question and harness type. The responses for the final comparison survey were just separated by question.

2.6 Statistical Analysis

The Analysis of Variance (ANOVA) technique was used to analyze the effects of the harness type and forward flexion angle on the normalized EMG using a statistical model. Assumptions of the ANOVA procedure (normality of residuals, independence, and homogeneity of residuals) were evaluated using the graphical techniques advocated by Montgomery (2001). A nonparametric analysis, specifically the Kruskal-Wallis test, was used to analyze the subjects' survey data. Throughout the analysis, a p-value of less than 0.05 indicated a significant effect.

2.6.1 Testing Assumptions of Analysis of Variance

The normality of residuals assumption of the ANOVA implies the residuals from the statistical model are normally distributed. To test for normality, the residuals, based on the statistical model, were plotted using a normal probability plot. The plots will resemble a straight line if the underlying error distribution is normal. In general, moderate departures, or slight skews, from the normality are acceptable and are of little concern in the fixed effects analysis of variance since the ANOVA is robust to the normality assumption (Montgomery, 2001).

The homogeneity of variances assumption is intended to ensure the model's residuals exhibit constant variance. If the statistical model is correct and the assumptions are satisfied, the residuals should have no structure and should be unrelated to any other variable, including the predicted response (Montgomery, 2001). To check for constant variance, the residuals were plotted as a function of the predicted values to ensure there was no systematic trend in the variability of the residuals as a function of the predicted values. To satisfy this assumption, the plot should not reveal any obvious pattern. In general, slight departures from the assumption are acceptable, because the F-test is only slightly affected due to the robustness of the model (Montgomery, 2001).

The independence assumption is used to ensure there is proper randomization of the experiment and the data collected from each subject is unrelated to the data from any other subject. The residuals from the statistical model for the study were plotted based on the trial number, 1 through 16, to detect if there were trends in the data set.

2.6.2 Analysis of Normalized EMG Data

A split-plot design model was used for the statistical analysis of the normalized EMG data, since the experimental trials could not be completely randomized. The linear model for the split-plot design is described by the equation below (Equation 1).

$$y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \gamma_k + (\beta\gamma)_{jk} + \varepsilon_{ijk} \qquad \text{Equation 1}$$

$$(i = 1\text{-}15,\ j = 1\text{-}2,\ k = 1\text{-}4)$$

The meaning of these variables is as follows:

y = EMG data

μ = expected mean value of EMG data

τ_i = block (subject)

β_j = harness type

$(\tau\beta)_{ij}$ = whole plot error

γ_k = forward flexion angle

$(\beta\gamma)_{jk}$ = interaction of harness type*angle

ε_{ijk} = subplot error

Following the analysis of variance, the Tukey-Kramer Honestly Significant Difference (HSD) post-hoc test was performed to determine the significant difference among forward flexion angle for the erector spinae and rectus abdominus muscles. Also, in those instances where there was both a significant interaction and a significant main effect, simple effects analysis was performed to verify that the main effect was significant across all levels of the other independent variable. If the main effect did not hold across all levels of the independent variable then only the interaction effect was considered.

2.6.3 Analysis of Survey Data

As the survey responses are classified as ordinal scales, a nonparametric one-way ANOVA was performed on these data. Namely, the Kruskal-Wallis test was used for the analysis. Equation 2 describes the statistical model used in this analysis

$$y_{ijk} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \qquad \text{Equation 2}$$

$$(i = 1\text{-}2,\ j = 1\text{-}15)$$

The meaning of these variables is as follows:

y = subject's response score

μ = expected mean value of response score

τ_i = harness type

β_j = block (subjects)

ε_{ij} = error

3 Results

The results are presented in three sections. Section 3.1 covers the results from the test of the analysis of variance assumptions. Section 3.2 presents the results from the statistical analysis and the normalized EMG data of the trapezius, erector spinae, and rectus abdominus muscles. Section 3.3 presents the results from the survey response data.

3.1 Test of the Analysis of Variance Assumptions

All of the analysis of variance assumptions were tested using the graphical methods advocated by Montgomery (2001). Refer to Appendix C for all the graphs. There were no violations for the normality and independence assumptions, but there was a potential violation in the homogeneity of variance for the erector spinae and rectus abdominus muscles, which can be seen in Figures 31 and 33. To correct the homogeneity of variance concerns, the log transformation, described by Montgomery (2001), was applied to the erector spinae and rectus abdominus muscles. Therefore, the subsequent statistical results for the erector spinae and rectus abdominus muscles are based on the log values instead of the actual values.

3.2 EMG Data

Table 2 displays the results from the statistical analysis of the EMG data for the trapezius, erector spinae, and rectus abdominus muscles, Tables 3 & 4 show the mean and standard deviations of the EMG data at the four different forward flexion angles for the NASA and the new harness, and Figures 20-22 show the interactions of harness type and angle. While the results presented in Table 2 related to the trapezius muscle indicate a significant main effect of harness type and angle, simple effects analysis revealed that neither harness type nor angle should be considered as the significant effect is fully described by the interaction. The results presented in Table 2 related to the erector spinae response likewise show a significant main effect for harness type and angle, and the simple effects analysis revealed that the main effect of angle should be considered significant while the harness type main effect was found to be fully addressed in the interaction. For the rectus abdominus muscles, the only effect that was statistically significant was the main effect of angle, which can be seen from Figure 22.

Table 2: Results of the ANOVA for the trapezius, erector spinae, and rectus abdominus muscles

	Trapezius		**Erector Spinae (Log)**		**Rectus Abdominus (Log)**	
	F - value	P - value	F - value	P - value	F - value	P - value
Harness Type	10.2966	0.0025*	17.9003	<.0001*	0.0022	0.9628
Angle	7.7171	<.0001*	204.8422	**<.0001***	16.4865	**<.0001***
Harness Type*Angle	3.5152	**0.0161***	5.1438	**0.0019***	0.2845	0.8366

*represents statistically significant difference between harness type (p< 0.05)

Note: Main effects shown in **BOLD** indicate simple effect

Table 3: The mean and standard deviations of the EMG data at the different forward flexion angles for the NASA harness

	Trapezius		**Erector Spinae**		**Rectus Abdominus**	
Angle	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev
15	2.98	1.54	8.45	3.55	13.15	6.91
30	3.04	1.51	15.01	5.42	15.19	10.12
45	2.68	1.43	17.11	5.71	19.05	16.98
60	2.60	1.45	21.68	8.48	21.71	19.88

Table 4: The mean and standard deviations of the EMG data at the different forward flexion angles for the new harness

	Trapezius		Erector Spinae		Rectus Abdominus	
Angle	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev
15	2.58	1.54	6.39	3.40	13.10	6.84
30	2.69	1.61	12.86	6.76	14.58	10.28
45	2.54	1.43	16.75	8.24	19.18	17.27
60	2.58	1.58	23.11	11.58	20.24	19.72

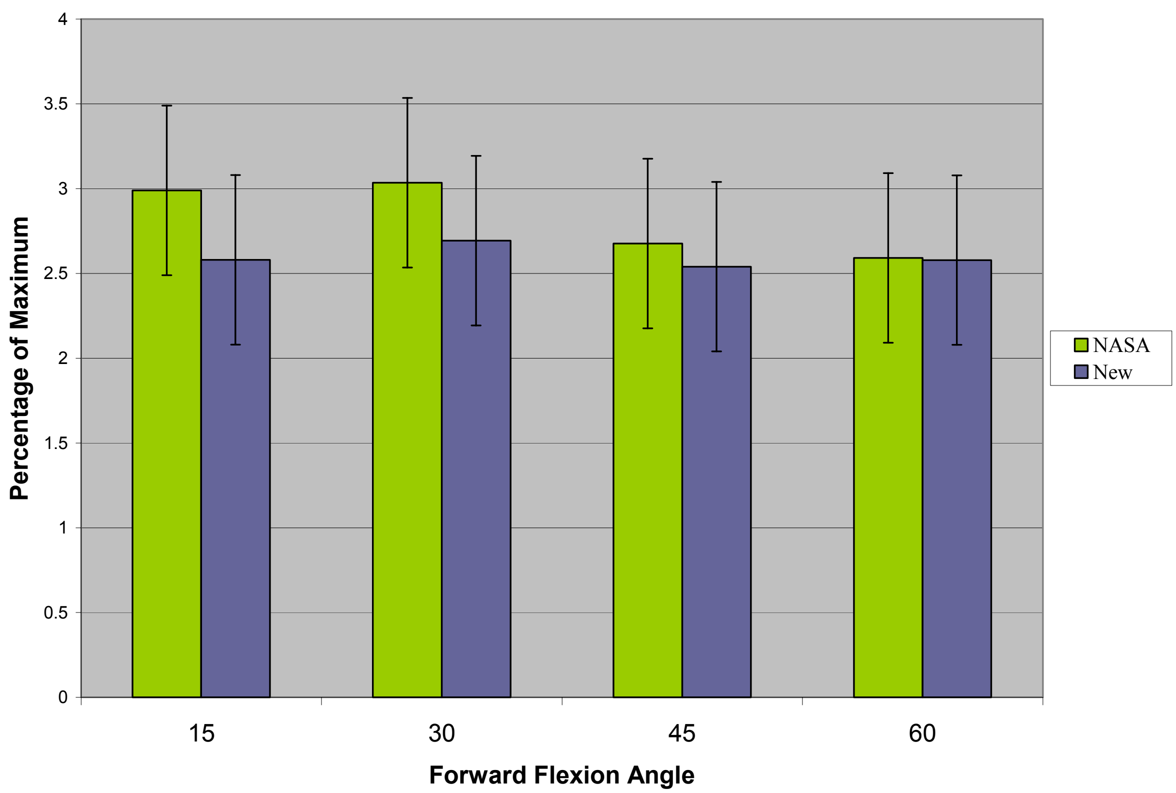

Figure 20: Normalized EMG of the trapezius muscles as a function of harness type and forward flexion angle

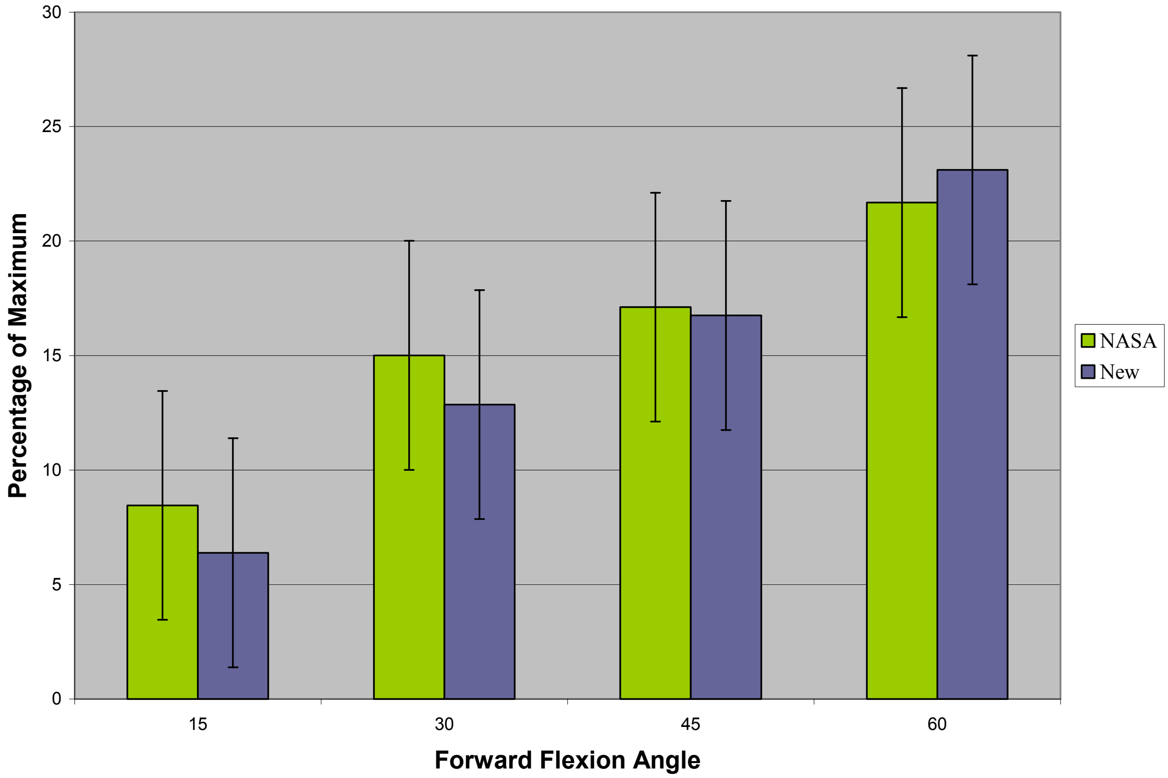

Figure 21: Normalized EMG of the erector spinae muscles as a function of harness type and forward flexion angle

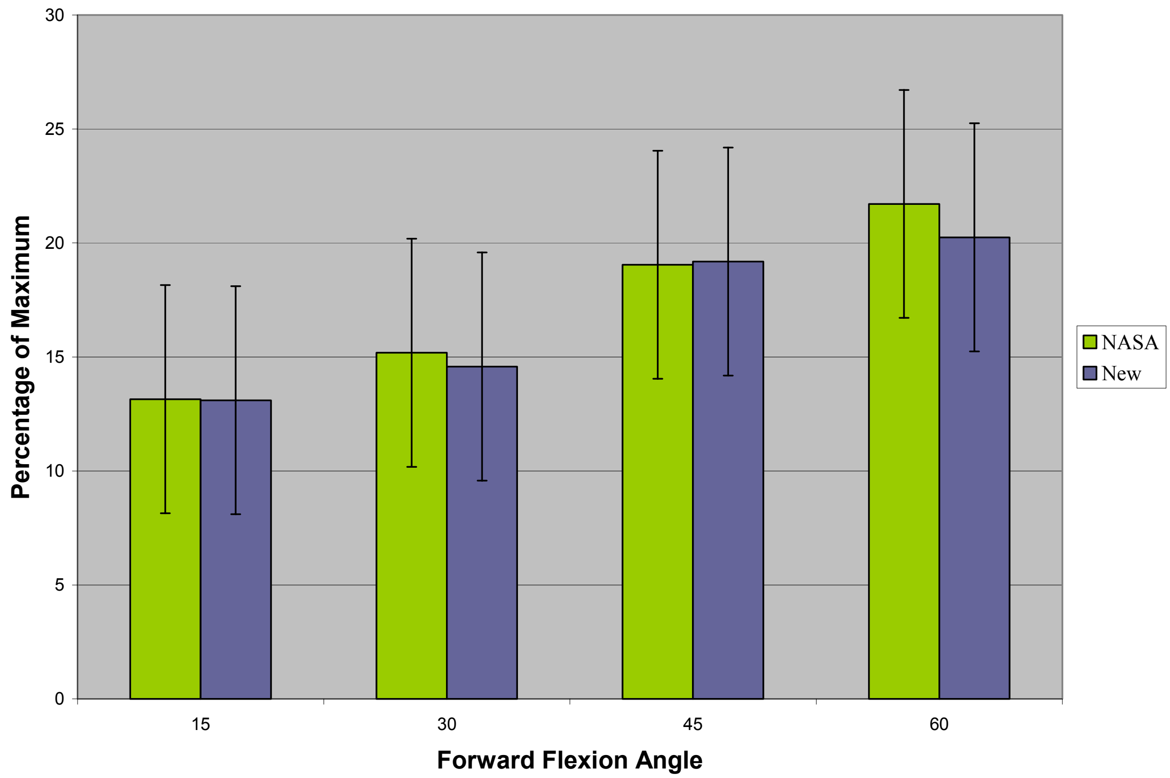

Figure 22: Normalized EMG of the rectus abdominus muscles as a function of harness type and forward flexion angle

Figures 20-22 also show the effect of harness type and forward flexion angle on the EMG activities of the trapezius, erector spinae, and rectus abdominus muscles. It should be noted that the forward flexion angles of 15 degrees and 30 degrees are the most important angles in the analysis, since these angles are the most common body positions the SCAPE employees put themselves in while completing the in work tasks. For the trapezius muscles at 15 and 30 degrees, the new harness had a 14% and 11% reduction, respectively in muscle activity compared to the NASA harness. For the erector spinae muscles at 15 and 30 degrees, the new harness had a 24% and 14% reduction, respectively in muscle activity compared to the NASA harness. For the rectus abdominus muscles, there was not a distinguishable difference in muscle activity between the two harnesses.

Since the main effect of angle on the trapezius muscles was due to the strong interaction effect of harness type*angle, a Tukey-Kramer HSD post-hoc test was not conducted for this muscle. However, the Tukey-Kramer HSD was conducted for the erector spinae and rectus abdominus muscles. For the erector spinae muscles, the test showed that all of the angles were significantly difference from each other. For the rectus abdominus muscles, the test showed that 15 degrees was statistically different from 45 and 60 degrees, and 30 degrees was statistically different from 45 and 60 degrees.

3.3 Survey Data

Table 5 displays the results from the statistical analysis of the survey data for the two post-test surveys. The table also shows a description of each of the four questions asked on the surveys, the mean score of each question for each harness, the results from the Kruskal-Wallis test, the chi-squared test statistic, and the corresponding probability value. The results of the Kruskal-Wallis test show that there was a significant difference between harness type for each question.

Table 5: Results of the Kruskal-Wallis Test for the post-test survey data

Question	Discomfort of…	Mean Score of NASA Harness	Mean Score of New Harness	Chi-squared statistic	Pr > Chi-squared
1	Shoulder straps on skin	2.6	1.8	18.5897	<.0001*
2	Trapezius muscles	3.1	1.9	15.3132	<.0001*
3	Low back muscles	2.8	1.9	14.4515	0.0001*
4	Overall	3.1	2.1	15.8572	<.0001*
*represents statistically significant difference between harness type (p< 0.05)					

The following graph (Figure 23) shows the average score of each question based on harness type. Recalling the range of the five points of scale, 1 = no discomfort, 3 = moderate discomfort, and 5 = very uncomfortable, the graph shows that there was more discomfort initially with the NASA harness than the new harness with respect to pressure on the shoulders of the skin (Question 1), the trapezius muscles (Question 2), and the erector spinae muscles (Question 3). With regards to overall comfort of the harness (Question 4), the graph also shows the NASA harness was initially perceived to be more uncomfortable then the new harness.

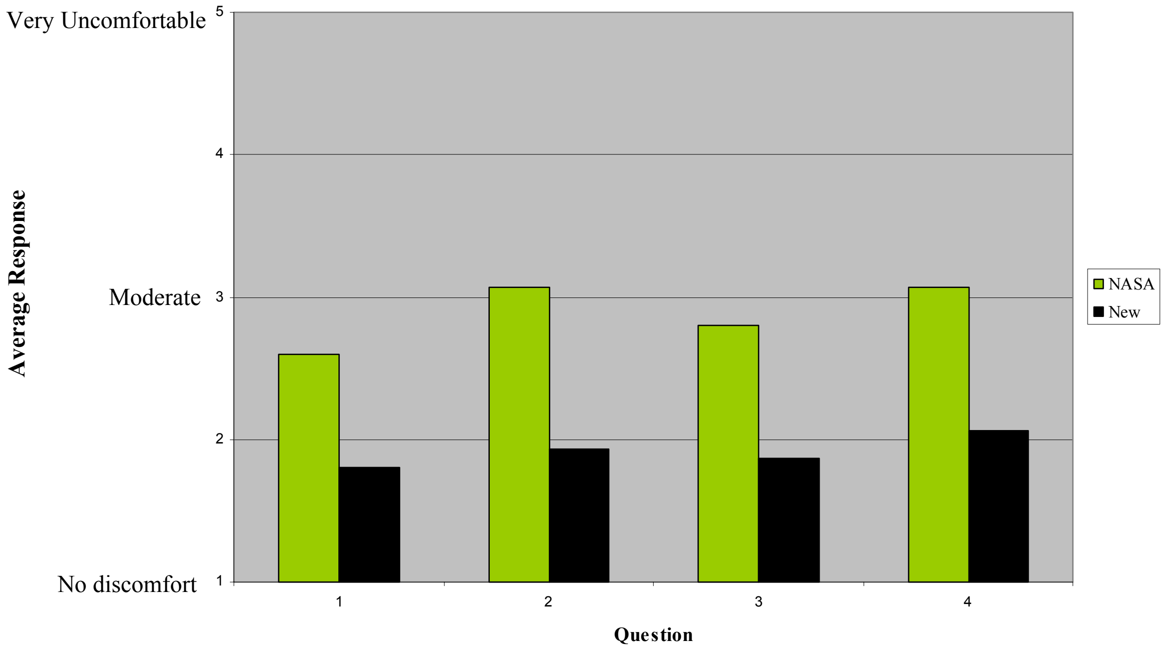

Figure 23: Average response of each question by harness type

For the final comparison survey, Figure 24 shows the mean score for each question. Recall that 1 was the value given if the subject thought the initial comfort/support of the NASA harness was "much worse" than the new harness, and 5 was the value given if the subject thought the comfort/support of the NASA harness was "much better" than the new harness. The results show an average score around 2, meaning the NASA harness is initially perceived to be "somewhat worse" than the new harness with respect to overall comfort, support of the harness while standing upright, and the support of the harness while leaning over at a 60 degree angle.

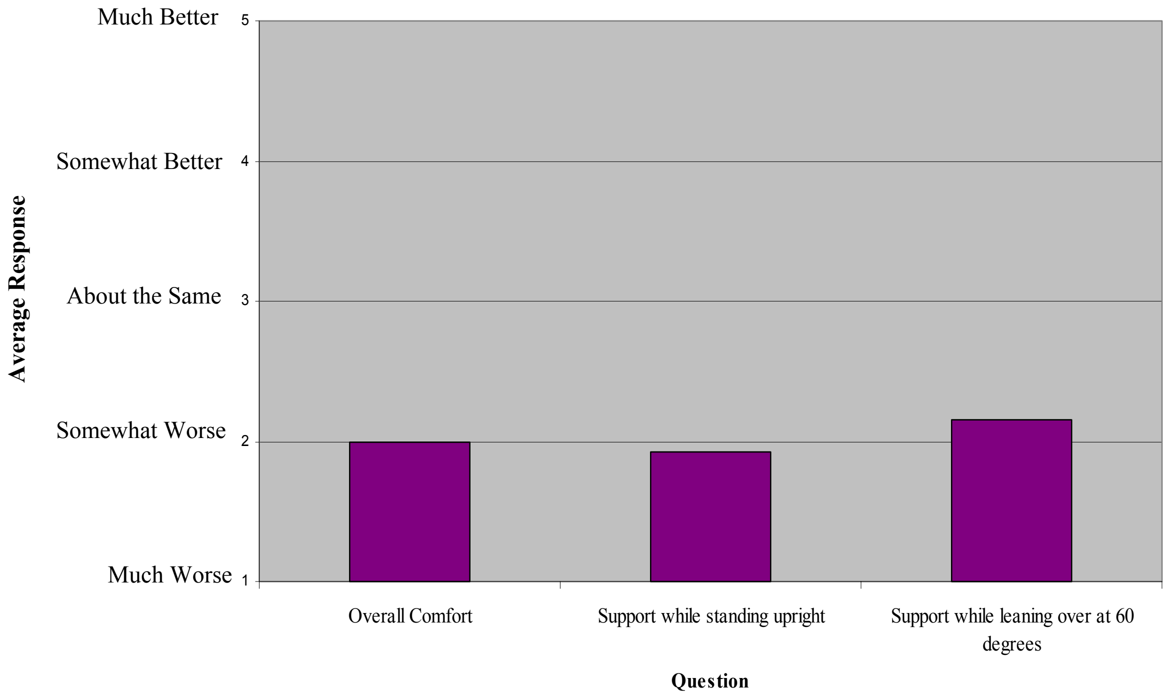

Figure 24: Average response of each question in the final comparison survey

4 Discussion

There were two hypotheses tested in the current study. The first hypothesis was that the new harness would reduce muscle activity of the trapezius, erector spinae, and rectus abdominus muscles. The second hypothesis was that the new harness would improve the comfort level in the shoulder region and the low back area. The following section discusses the results related to these hypotheses, how each hypothesis relates to the SCAPE employees' complaints and the backpack literature, overall recommendations, the limitations of the current study, and future research.

It is important to note that the four forward flexion angles of 15, 30, 45, and 60 degrees were chosen based on the interview conducted with the five SCAPE employees and the video tape that was analyzed. Since all of the SCAPE employees stated they spend most of their time while in the SCAPE suit performing tasks while walking, the forward flexion angle of 15 degrees was of most concern in the biomechanical analysis. The 15 degree angle was considered to be the neutral angle while walking and standing with a load placed on the back, since there is a slight forward lean of the torso to stabilize and balance the body and the load's center of mass over the feet (Bloom & Woodhull-McNeal., 1987; Knapik et al., 1996; Vacheron et al., 1999). The 30 degree angle was considered to be another common position, since the video showed the employees spending time at this forward flexion angle while performing a particular task. Also, since most research on backpacks has focused on the traditional upright posture while wearing the backpack, the forward flexion angles of 45 and 60 are also of importance to see how low back muscles are affected by steep non-neutral postures while wearing a backpack.

Hypothesis 1: The new harness will decrease the activity of the trapezius, erector spinae, and rectus abdominus muscles compared to the existing NASA harness.

The simple effects analysis for the trapezius muscles revealed that the interaction effect was responsible for the significant main effect of harness type and forward flexion angle. This result is logical since the NASA harness is only significantly different than the new harness at the angles of 15 and 30 degrees, and also that the new harness is not affected by angle at all. A reason why the NASA harness shows a significant difference at the 15 and 30 degree angles than the new harness is that the design of the NASA harness transfers most of the weight of the ECU to the shoulders, while the new harness takes more of the weight off of the shoulders and focuses it more on the hips. The results also show that there is not a significant difference between the two harnesses at the angles of 45 and 60 degrees, which is due in part to the fact that while leaning over in these steeper angles, more of the weight of the ECU is focused on the mid to low back and not as much on the shoulders. The normalized EMG data for the trapezius muscles shows that the muscle activity of the NASA harness at 15 and 30 degrees were 2.9% and 3.0%, respectively. Meanwhile, the muscle activity of the new harness at the 15 and 30 degrees were 2.6% and 2.7%, respectively, showing that there is a reduction in trapezius muscle activity while wearing the new harness. The significance of these results are somewhat surprising considering the nature of the experiment, because the subjects were asked to keep their arms across and around their stomach region when they were positioned at each of the four forward flexion angles, so there was little activation, if any, of the trapezius muscles during the entire experiment. In SCAPE activities however, some tasks require abduction of the shoulders and doing work with the arms above the head. So even though the trapezius muscles were not being activated, the new harness did reduce the amount of weight that is placed on the shoulders from the shoulder straps when the body is positioned at the 15 and 30 degree forward flexion angles.

For the erector spinae muscles, the simple effects analysis revealed that the main effect of angle is significant, while the interaction effect was responsible for the significant main effect of harness type. The main effect of angle was expected since the erector spinae muscle activity increases for both harnesses as a function of angle. Plus, the increase in forward flexion angle has a major impact on erector spinae muscles, because the percentage of erector spinae muscle activity must also increase, since the erector spinae muscles are activated to help keep the torso at the desired angle without falling over. The normalized EMG data also shows this trend, along with a slight reduction in erector spinae muscle activity when wearing the new harness compared to the NASA harness. While wearing the NASA harness, the erector spinae muscle activity at 15 and 30 degrees were 8.4% and 15%, respectively. Meanwhile, the muscle activity of the new harness at 15 and 30 degrees were 6.4% and 12.9%, respectively, which shows the reduction in erector spinae muscle activity while wearing the new harness. The results for the 60 degree forward flexion angle were somewhat surprising, since the new harness actually showed a higher normalized EMG compared to the NASA harness. However, after performing a main effects analysis of harness type at the 60 degree angle, the statistical results showed that harness type was not statistically significant at this position, and therefore these results are not a cause for concern.

As for the rectus abdominus muscles, there was only a statistically significant difference on forward flexion angle, which was expected, since the rectus abdominus muscles help support the body in non-neutral postures by maintaining spinal stability. The normalized EMG shows this significance of forward flexion angle, and that there is not a significant reduction of muscle activity between the two harnesses. A possible explanation for these results is that the rectus abdominus muscles are responsible for holding the torso in place and keep the person from falling over backwards. Therefore, the type of harness did not have an impact on the rectus abdominus muscle activity. Since the position of the ECU was the same for both harnesses, the rectus abdominus muscles exerted about the same amount of muscle activity for each harness at each angle.

The results of the normalized EMG for the trapezius, erector spinae, and rectus abdominus muscles reflect the complaints of the SCAPE employees and the backpack literature. From the personal interviews with the five SCAPE employees, the main complaint was the discomfort or pressure of the shoulder straps of the NASA harness on the shoulder region. Even though low back pain was not perceived to be a major source of discomfort, research has shown that back problems account for 22% of all load carriage injuries (Knapik et al., 1992). The forces/stresses and moments experienced by the spine and back muscles created by the weight of the ECU on the back are causes for concern and could pose potential risks and hazards to the low back over a period of time. So even though the SCAPE employees may not feel any discomfort now, they may start to have low back pain later on in life, which may be a result of the weight of the ECU and how the load is carried on the back.

Previous research (LaFiandra et al., 2004; Knapik et al., 1996; Holewign, 1992; Stevenson et al. (2004a)) has shown that a hip belt improves performance of certain upper body tasks during load carriage and can actually reduce the amount of pressure on the shoulders by displacing the major mass of the load from the shoulders to the hips. In addition to hip belts, lateral stiffness rods have also shown to play a role in transferring the weight of the load off the shoulders and onto the hips. Figures 25 shows a diagram of the lateral stiffness rods unengaged. Figure 26 shows a diagram of the lateral stiffness rods engaged with the force vectors showing load distribution. Lateral stiffness rods provide a stiffer suspension to help transfer weight of the load from the shoulders and upper back to the hips (Reid et al., 2004; Stevenson et al., 2004b). When a lateral stiffness rod is engaged, the rod creates a moment about the fixed point. The rod then "tries" to straighten out to release its tension, forcing the weight of the ECU up, resulting in more weight transferred to the fixed point and less weight placed on the shoulders via the shoulder straps. The lateral stiffness rods have also shown to increase the extensor moment, which reduces the likelihood of the forward flexion of the torso. Since there is a reduction of forward flexion angle due to the fact that a person can stand more upright, the amount of erector spinae muscle activity decreases and may delay the onset of muscular fatigue in the back (Stevenson et al., 2004b). Since SCAPE employees are suited up with the ECU on for a maximum of two hours, being able to possibly delay the onset of muscular fatigue would definitely benefit the SCAPE employees and may reduce the potential risk for low back pain in the future.

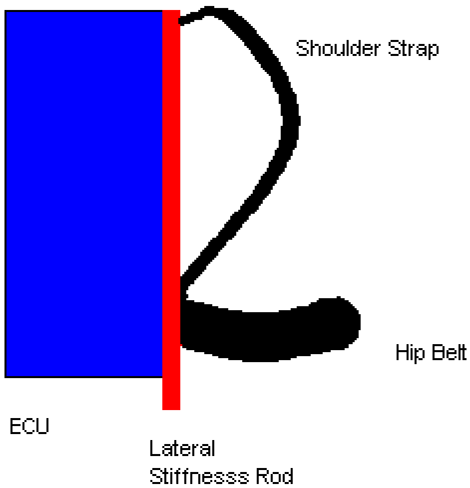

Figure 25: Lateral stiffness rods unengaged

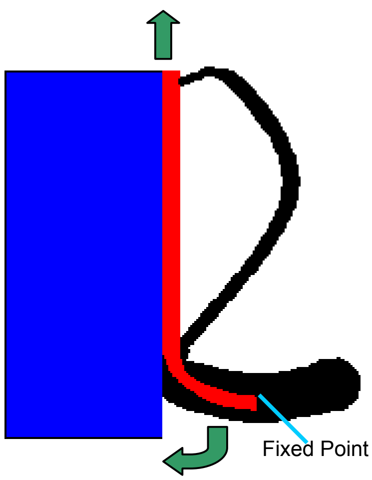

Figure 26: Lateral stiffness rods engaged and force vectors showing load distribution.

The findings of the backpack literature correspond with the results of the current study in that the use of a hip belt in combination with lateral stiffness rods is one of the most important system components of a supportive harness. The NASA harness does not have a supporting structure of any kind on the hips, so most of the ECU's weight is placed on the shoulder region via the shoulder straps, which in turn puts a lot of stress on the low back.

These stresses can be seen from the normalized EMG results of the trapezius and erector spinae muscles. On the other hand, the new harness has both a supporting hip belt and lateral stiffness rods, to make sure most of the weight of the ECU is placed on the hips. This system alleviates some of the stress experienced by the trapezius and the erector spinae muscles, and therefore reduces the amount of muscle activity while one wears the new harness compared to the NASA harness. Thus, the results of the EMG data on the trapezius and erector spinae muscles agree with previous research, which has shown that the use of a hip belt transfers approximately 30% of the vertical force of the backpack to the hips (LaFiandra et al., 2004; LaFiandra & Harman, 2003), and that lateral stiffness rods have shown to transfer 14% the vertical load from the upper back and shoulders to the hips (Reid et al., 2004; Stevenson et al., 2004b).

While carrying a load on the back, there are important design criteria from a biomechanical modeling standpoint that have been researched to limit the risk for low back problems. Stevenson et al. (2004a) developed a back pack design criterion for reducing the forces and moments on the back. The load should be focused on the hips via a hip belt to minimize the pressure on the shoulders caused by the straps. Additionally, lateral stiffness rods should be used to help transfer the load to the hips. The load should be positioned around T1-T6 region, making its center of mass as close to the body as possible. Lastly, the harness should ensure stability. All of these criteria have been addresses in the new harness system, making it a better support system than the NASA harness.

In addition to the effects of a hip belt, the placement of the load has shown to have an effect on trapezius and erector spinae muscle activity. Bobet & Norman (1984), Stuempfle et al. (2004), and Stevenson et al. (2004a) all suggest placing the load around the T1-T6 region instead of the C1-C7 region. Placing the load around the T1-T6 region places the load's center of mass as close to the body as possible, therefore lowering the muscle activity of the trapezius and erector spinae muscles. Also, as the forward flexion angle increases, the placement of the load around the T1-T6 region generates a moment smaller about L5/S1 than placing the load at the C1-C7 region. Placing the load at C1-C7 actually increases erector spinae muscle activity at steeper forward flexion angles, since the moment about L5/S1 is larger due to the higher position of the load on the spine. Therefore, the T1-T7 position has been shown to be the most efficient and desirable mode for carrying a load on the back. Additionally, it reduces physiological responses of the body while performing certain tasks. Both harnesses tested were position the ECU the around the T1-T6 region, which reduces the risk for low back pain by reducing erector spinae muscle activity.

Carrying a load on the back can also have an impact on the curvature of the spinae, as shown by Orloff & Rapp (2004). They found that there was a significant increase in the curvature of the spine from the thoracic to the lumbar region as a function of fatigue. This increase in curvature can cause an increase in the moments about L5/S1 and the compressive forces on the intervertebral discs. Since the SCAPE employees are suited up for a maximum of 2 hours, it is important to take this information into consideration to make sure that the harness used while performing a SCAPE operation is design properly and efficiently as to limit the amount of stress placed on the low back.

Using Stevenson et al.'s (2004a) design criteria, other findings from previous researchers, and the results of this study, it is easy to notice there are some concerns to the design features to the design of the NASA harness. The most important feature that stands out is the need for a supportive hip belt in combination with lateral stiffness rods, which is where the new harness becomes a better design from a biomechanical standpoint.

Hypothesis 2: The new harness would improve the comfort level in the shoulder region and the low back area.

Recall that the subjective survey's responses regarding the comfort level of each harness was based on the initial perception of comfort for each subject. Therefore, assumptions cannot be made regarding the comfort level for the expected wear duration of 2 hours based on such a short period of exposure to the both harnesses.

For the post-test surveys, all four questions for each harness produced statistically significant results between harness type. The average mean response score for Question 1, which asked the discomfort level on the skin of the shoulders, was 2.6 for the NASA harness and 1.8 for the new harness. These results show that the subjects initially perceived the new harness to be more comfortable in the shoulder area. For Question 2, which asked the discomfort level felt on the trapezius muscles, the average mean scores for the NASA and the new harness were 3.07 and 1.93, respectively. These results, again, show that the subjects initially perceived the new harness to be more comfortable than the NASA harness for the trapezius muscles. The results for the first two questions, which are confirmed with the EMG results for the trapezius muscles, show that the combination of a hip belt and lateral stiffness rods in a harness can make the weight of the ECU more bearable to wear, since the weight of the load is focused more on the hips instead of the shoulders. For Question 3, which asked the discomfort felt on the low back, the average mean response scores for the NASA and the new harness were 2.8 and 1.87, respectively. Once again, the subjects initially perceived that while wearing the new harness, the weight of the ECU caused less stress in the low back area compared to the NASA harness. These results also agree with the EMG results, which show the NASA harness caused more muscle activity in the erector spinae muscles than the new harness. With regards to overall comfort of a harness, Question 4, the average mean score for the NASA harness and the new harness were 3.07 and 2.07, respectively. So overall, the subjects initially perceived the new harness to be more comfortable to wear than the NASA harness.

The third survey that was given to each subject after they had worn both harnesses was the final comparison survey. In this survey, the subjects were asked to compare the NASA harness to the new harness with respect to overall comfort level, the comfort level while standing up in the neutral, or 15 degree, position, and the comfort level while leaning over at the 60 degree position. Recall that 1 was the value given if the subject thought the comfort/support of the NASA harness was "much worse" than the new harness, and 5 was the value given if the subject thought the comfort/support of the NASA harness was "much better" than the new harness. The average score for each of these questions was a 2, meaning that, overall, the subjects initially perceived the NASA harness to be "somewhat" worse than the new harness.

Overall Recommendations

Since SCAPE employees complete 2 to 3 operations during a 10-12 hour shift, and they suit up for a maximum of 2 hours, it is very important to make sure that they are able to perform each task accurately and as efficiently as possible. Although environmental variables may hinder task performance, discomfort from the SCAPE suit, specifically the harness system that holds the ECU, could also affect task performance. When a task is not performed correctly, or in this case is not performed in the time allotted, it could affect costs, task schedules, and the overall SCAPE program itself.

Not only is task performance important, but the health and safety of all of the SCAPE employees is extremely important. The health and safety of the employees affects all aspects of the SCAPE program. If the SCAPE employees are at a risk for shoulder or low back problems, or other potential hazards, it will not only affect their performance, but it could become a costly situation. If an employee is injured or develops a musculoskeletal disorder while on the job, worker's compensation comes into the picture and could become a major expense for the program. Plus, the number of healthy employees would also decrease, so the healthy employees may have to step up and do more operations. In turn, this could lead to the healthy employees becoming more susceptible to injuries or developing musculoskeletal disorders.

The SCAPE employees that were interviewed said that after a SCAPE operation, they felt like they had just finished a "very tiring workout." Although this may be the case now, if they are feeling discomfort in their shoulder or low back areas during their SCAPE operations, over a period of time, these discomforts could possibly lead to development of musculoskeletal disorders in their shoulders or low back. If these potential risks could be prevented or reduced with the addition of a more supportive harness for the ECU, not only the employees themselves would benefit, but also the SCAPE program and NASA itself.

Limitations

The first limitation of this study is that the subjects did not perform any dynamic activities while wearing either harness. Although the subjects walked a few steps while in each harness, they never moved around in the harness except when positioning their torso in the specified forward flexion angle while standing still. For example, the subjects never squatted on their knees, crawled on their hands and knees, or walked around any length of time while wearing each harness (which are activities that occur during a routine SCAPE operation). It is possible that these dynamics activities could have shown even more significant differences between harness types or impacted the perception of the comfort level of each harness. Since EMG was used to examine the muscle activities of each subject while wearing each harness, the data must be recorded when the subject is in a static steady-state position, because dynamic activities can create a lot of noise in the EMG data. For future research, the next logical step would be to have the subject complete dynamic tasks that simulate some of the common tasks that are in SCAPE operations, and to get a more accurate assessment on the comfort level of each harness.

The second limitation of this study is that the subjects only spent approximately 10 minutes in each harness while performing the experimental task. Since the purpose of the study was to examine the magnitude of the amount of muscle force required to hold a specified position while wearing each harness, having the subjects hold a position for 5 seconds (once a person has reached steady state) was sufficient to establish how hard the muscles must work to maintain that position. Ideally, if the subjects were to wear each harness for a maximum of two hours, just like they do a typical SCAPE operation, this may impact the perception of the comfort level of each harness.

The third limitation of this study is the laboratory setting. If the experiment could have been conducted as field research, with the actual SCAPE employees wearing each of the harnesses while performing their usual SCAPE tasks, the subjective results may have differed since the SCAPE employees are used to wearing 40 lbs on their backs while doing their job. Time, costs, and the fact that SCAPE operations are performed down at the Kennedy Space Center were all factors in the decision to perform the experiment in the laboratory with regular people as the subjects.

Future Research

Future research should address the limitations of the current study along with addressing the effect of doing overhead work (shoulder flexion activities) on the trapezius muscles while wearing each harness. Since both harnesses put some weight on the trapezius muscles, and some common SCAPE tasks require overhead work, it is important to analyze how shoulder flexion would impact the trapezius muscles while wearing both harnesses. Even though the results in the current study showed there was a slight effect of harness type on the trapezius muscles at the 15 and 30 degree forward flexion angles, these muscles were hardly, if at all, being used. It would be interesting to see if the new harness improved the range of motion of the shoulders and arms, since more of the weight was taken off the shoulders while wearing the new harness compared to the NASA harness.

5.0 Conclusion

The objective of this study was to evaluate the effects of a newly designed harness and the current NASA SCAPE harness in terms of biomechanical loading and subjective assessment by the user. A new harness was developed based on recommendations from the backpack literature with considerations given to the limitations presented by the attachment points to the ECU. It was hypothesized that the new harness would reduce the muscle activity of the trapezius, erector spinae, and rectus abdominus muscles, and would also improve the comfort level in the shoulder and low back area.

To test the biomechanical effects of the NASA harness and the new harness, subjects were required to lean their torso over in four different forward flexion angles (15, 30, 45, and 60 degrees) while EMG was recorded. The subjects were then asked to fill out subjective surveys based on the comfort level of each harness. The EMG results showed the new harness reduced the activity of trapezius and erector spinae muscles at 15 degrees by 14% and 24%, respectively, and at 30 degrees by 11% and 14%, respectively. The subjective surveys also agreed with the EMG results, in which the subject stated that the new harness was more comfortable with respect to the shoulder and low back areas, as well as overall comfort.

In conclusion, it can been seen that the new harness reduces the trapezius and erector spinae muscle activity, as well as improving the comfort level in the shoulder and low back areas. The new harness includes a supportive hip belt with lateral stiffness rods, which allows the weight of the ECU to be transferred from the shoulders to the hips, whereas the NASA harness does not have any kind of hip belt, so most of the weight is placed right on the shoulders. Therefore, upon evaluation of the subjective and objective results for both harnesses, the new harness shows a significant improvement over the NASA harness.

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Appendix A: Informed Consent Form

North Carolina State University
INFORMED CONSENT FORM for RESEARCH

Title of Study: The biomechanical loading effects of the existing SCAPE backpack harness and a redesigned harness

Principal Investigator: Stephanie Southard Faculty Sponsor (if applicable) : Dr. Gary A. Mirka

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We are asking you to participate in a research study. The purpose of the study is compared the biomechanical loading effects of the existing NASA Self Contained Atmospheric Protective Ensemble (SCAPE) backpack harness to a new harness that was developed at NC State. You should not participate in this study if you have any chronic or current problems/discomfort in your back or hips. If you do NOT have such an injury or disease, please initial here: __________.

INFORMATION

If you agree to participate in this study, you will be asked to perform following tasks.

After you sign this informed consent form, you will have a brief warm-up period and some simple body measurements will be collected. You will be asked to participate in a 90 minute experiment. Six pairs of surface electrodes will be placed on your low back, trapezius (shoulder area), and rectus abdominus (stomach area) using double-sided adhesive tape. Electrode attachment sites may need to be shaved for better contact. Once all electrodes are securely placed, your maximum trunk extension force and EMG muscle activity will be collected while you push and pull as hard as you can against a bar with your upper back. You will perform a maximum trunk extension for four different angles, repeating the same angle once, for a total of 8 maximum trunk extensions. You will them perform a maximum exertion for the trapezius muscles by shrugging your shoulders by pulling a chain that is perpendicular to the floor. Following a five minute break, you will carry a box of 40 lbs, equally distributed, on the back by means of a harness. You will angle your torso at 4 different angles, each for 5 seconds, repeating each angle twice, and you will also get a 1 minute break between data collection. You will perform this task for both harnesses. You will be asked to fill out a subjective survey after you perform the experiment for each harness, and then a final comparison survey.

RISKS

Since this research involves maximum back exertions and you will have to position your trunk in forward flexion angles while carrying 40 lbs in a pack, you may feel fatigue in the low back and shoulders during or after the experiment (possibly lasting for several days as you might after a strenuous workout). There is also a potential for more serious injury due to these factors. If you experience pain during the experiment, notify the experimenter immediately.

BENEFITS

Your participation will help compared the biomechanical effects of the existing SCAPE harness to the modified harness. These results and design recommendations will be presented to NASA, to show that the modified harness alleviates some of the stresses experienced by the current SCAPE employees.

CONFIDENTIALITY

The information in the study records will be kept strictly confidential. Each subject will be assigned a number, by which the subject's data and information will be referenced. This list and all other data will be stored securely and will be made available only to persons conducting the study. After the experiment is complete (data processed, statistical analysis performed, and report written) the list of the subject's names and numbers will be destroyed. No reference will be made in oral or written reports which could link you to the study.

Appendix A: Informed Consent Form

EMERGENCY MEDICAL TREATMENT

There is no provision for free medical care for you in the event that you are injured during the course of this study. In the event of an emergency, medical treatment may be available through Student Health Service on campus or through the 911 emergency response services.

CONTACT

If you have questions at any time about the study or the procedures, you may contact the researcher, Stephanie Southard, at Riddick Lab Room 335, Stinson Ave, North Carolina State University, or [919-515-7210]. If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Dr. Matthew Zingraff, Chair of the NCSU IRB for the Use of Human Subjects in Research Committee, Box 7514, NCSU Campus (919/513-1834) or Mr. Matthew Ronning, Assistant Vice Chancellor, Research Administration, Box 7514, NCSU Campus (919/513-2148)

PARTICIPATION

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed at your request.

CONSENT

"I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may withdraw at any time."

Subject's signature____ **Date** _________________

Investigator's signature___________________________________ **Date** _________________

Appendix B: Subjective Surveys

Subjective Survey – Green Harness

Date: ________________________ Subject: _____________________

1) Please rate the discomfort level you felt from the shoulder straps on the skin of the shoulders while wearing the green harness.

1	2	3	4	5
No discomfort		Moderate		Very Uncomfortable

2) Please rate the discomfort level you felt on the trapezius muscles (shoulders) while wearing the green harness.

1	2	3	4	5
No discomfort		Moderate		Very Uncomfortable

3) Please rate the discomfort level you felt on the low back while wearing the green harness.

1	2	3	4	5
No discomfort		Moderate		Very Uncomfortable

4) Overall, how would you rank the comfort of the green harness?

1	2	3	4	5
Comfortable		Moderate		Very Uncomfortable

5) If you felt discomfort in other places of the body besides the places mentioned above, please list them here and rank the discomfort level for each.

____

____

____

Appendix B: Subjective Surveys

Subjective Survey – Black Harness

Date: ________________________ **Subject: _____________________**

1) Please rate the discomfort level you felt from the shoulder straps on the skin of the shoulders while wearing the black harness.

1	2	3	4	5
No discomfort		Moderate		Very Uncomfortable

2) Please rate the discomfort level you felt on the trapezius muscles (shoulders) while wearing the black harness.

1	2	3	4	5
No discomfort		Moderate		Very Uncomfortable

3) Please rate the discomfort level you felt on the low back while wearing the black harness.

1	2	3	4	5
No discomfort		Moderate		Very Uncomfortable

4) Overall, how would you rank the comfort of the black harness?

1	2	3	4	5
Comfortable		Moderate		Very Uncomfortable

5) If you felt discomfort in other places of the body besides the places mentioned above, please list them here and rank the discomfort level for each.

____

____

____

Appendix B: Subjective Surveys

Final Survey – Comparison of Harnesses

Date: ________________________ **Subject: _____________________**

1) With regard to overall comfort, how would you rate the green harness to the black harness?

1	2	3	4	5
Much Worse	Somewhat Worse	About the Same	Somewhat Better	Much Better

2) When standing upright, how would you rate the support of the green harness compared to the black harness?

1	2	3	4	5
Much Worse	Somewhat Worse	About the Same	Somewhat Better	Much Better

3) When leaning forward in the 60 degree angled position, how would you rate the support of the green harness compared to the black harness?

1	2	3	4	5
Much Worse	Somewhat Worse	About the Same	Somewhat Better	Much Better

Appendix C: Graphs for the Assumptions of the Analysis of Variance

Test for Normality of Residuals

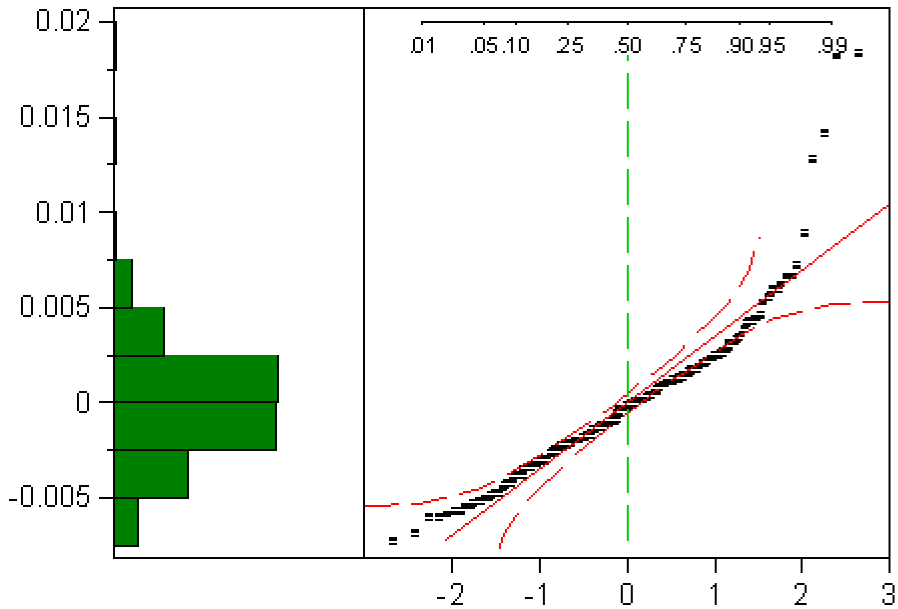

Figure 27: The normal quantile plot of the residuals for the trapezius muscles.

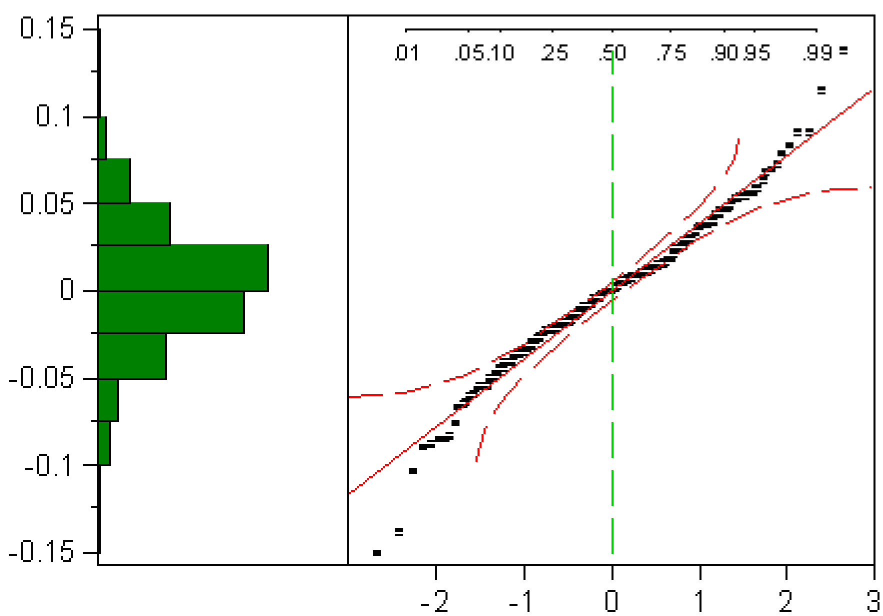

Figure 28: The normal quantile plot of the residuals for the erector spinae muscles.

Appendix C: Graphs for the Assumptions of the Analysis of Variance

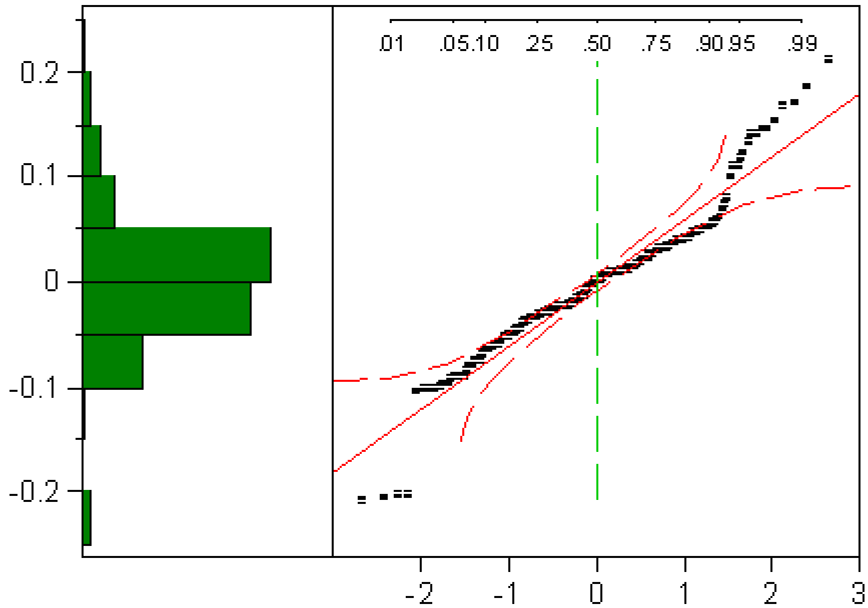

Figure 29: The normal quantile plot of the residuals for the rectus abdominus muscles.

Test for Homogeneity of Variances

Appendix C: Graphs for the Assumptions of the Analysis of Variance

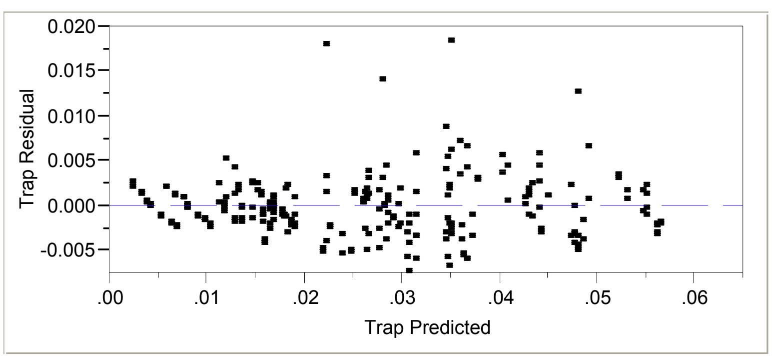

Figure 30: Scatter plot of the residuals as a function of the predicted values for the trapezius muscles

Appendix C: Graphs for the Assumptions of the Analysis of Variance

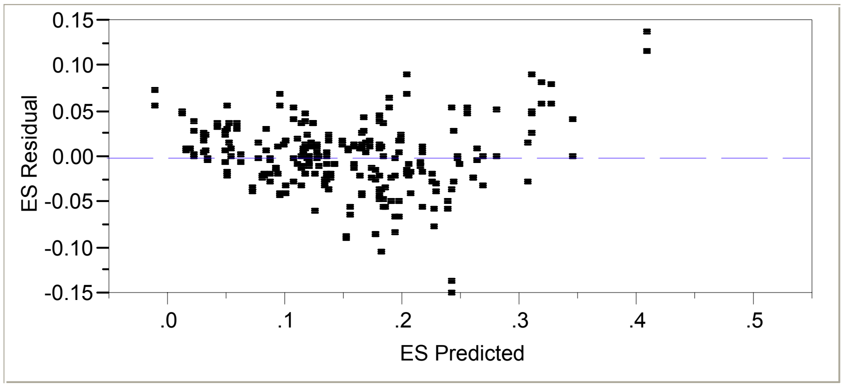

Figure 31: Scatter plot of the residuals as a function of the predicted values for the erector spinae muscles

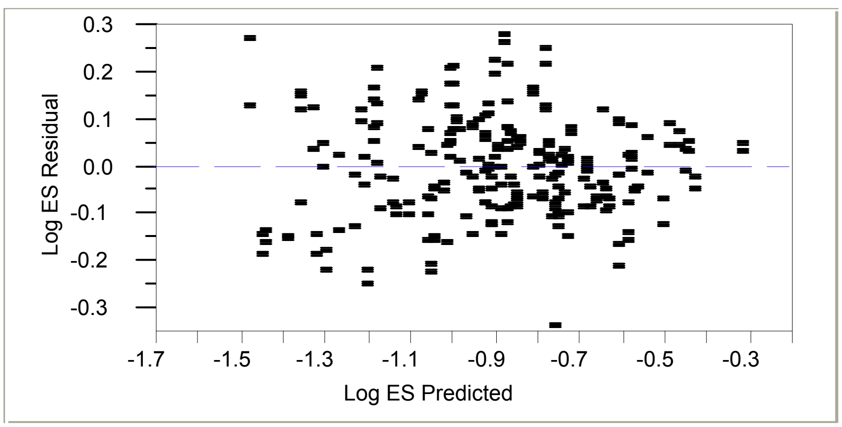

Figure 32: Scatter plot of the residuals as a function of the predicted values for the erector spinae muscles using the log transformation values

Appendix C: Graphs for the Assumptions of the Analysis of Variance

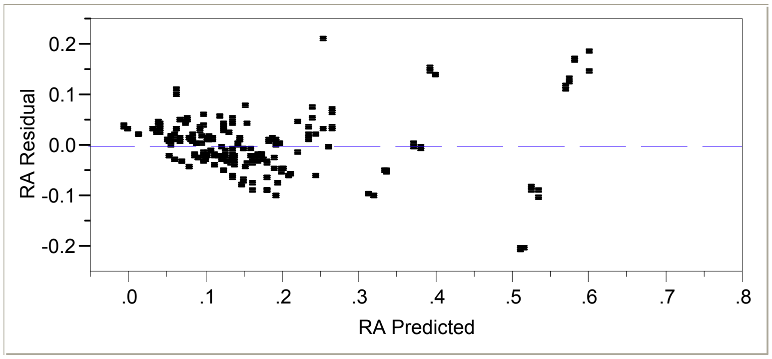

Figure 33: Scatter plot of the residuals as a function of the predicted values for the rectus abdominus muscles.

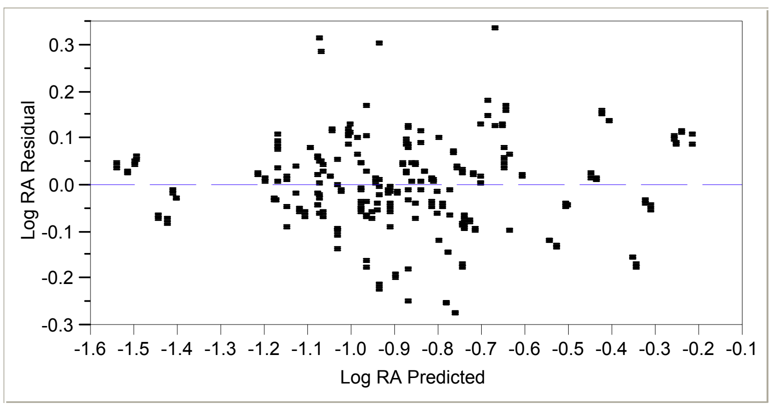

Figure 34: Scatter plot of the residuals as a function of the predicted values for the rectus abdominus muscles using the log transformation values

Appendix C: Graphs for the Assumptions of the Analysis of Variance

Test for Independence

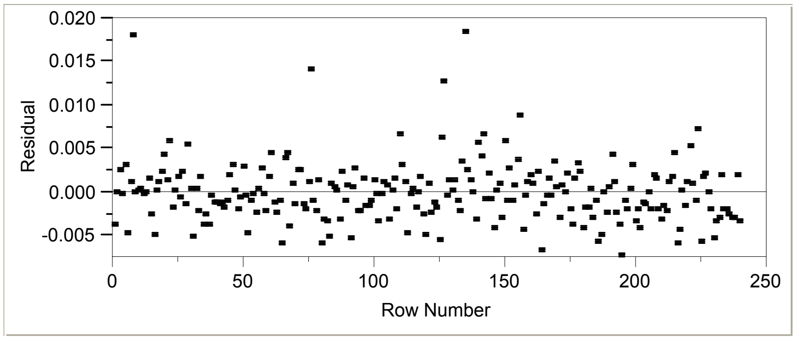

Figure 35: Scatter plot of the residuals to test the independence between trials for the trapezius muscles.

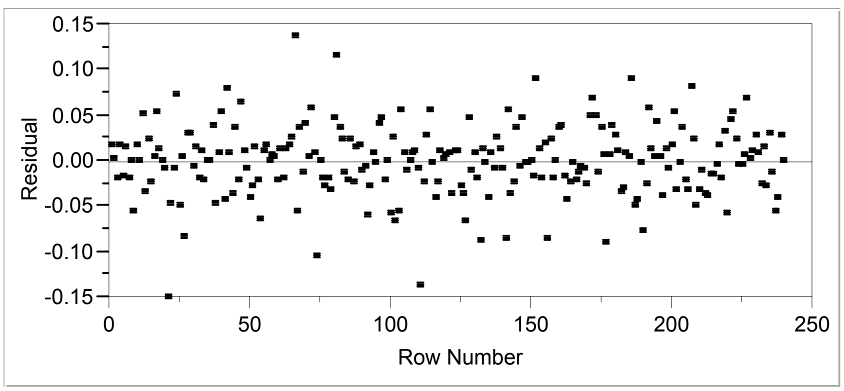

Figure 36: Scatter plot of the residuals to test the independence between trials for the erector spinae muscles.

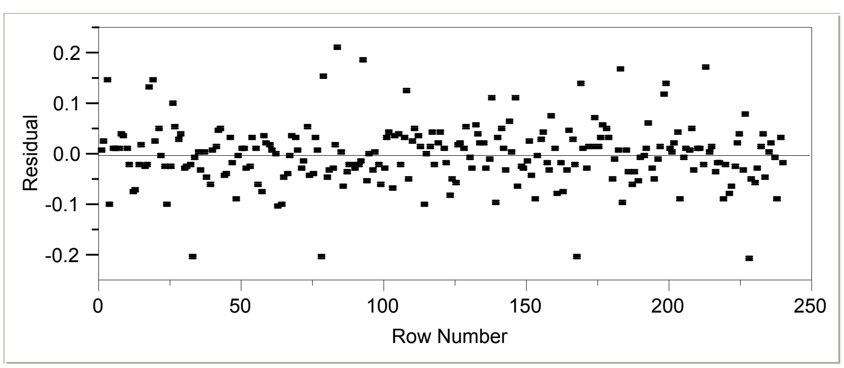

Figure 37: Scatter plot of the residuals to test the independence between trials for the rectus abdominus muscles.