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An evaluation of backpack harness systems in non-neutral torso postures

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Abstract

Much of the research on backpack design has been focused on spinal loading/biomechanics while the wearer is in a neutral/upright trunk posture, such as those employed by outdoor enthusiasts and schoolchildren. This research has led to some important harness design improvements that reduce trunk muscle exertions, fatigue and improve overall comfort. There are number of occupations, however, wherein workers wear back-mounted packs/devices (e.g. air tanks) while working in non-neutral trunk postures. The objective of the current study was to evaluate the effects of these non-neutral postures on biomechanical loading and then reconsider the backpack system design recommendations. Fifteen participants were asked to support a 18.2 kg load on their back while assuming static forward flexed postures of the torso (15°, 30°, 45°, and 60° of sagittal bend). The mass on the back was attached to the participant through two different harness mechanisms: a basic harness design (as seen on college student backpacks) and a more advanced design containing lateral stiffness rods and a weight-bearing hip belt (as seen on backpacks for hikers). While performing these static, posture maintenance tasks, the activation levels of the bilateral trapezius, erector spinae, and rectus abdominis were collected. Participants also provided subjective ratings of comfort. The results showed that there was a significant interaction between harness type and forward flexion angle for the trapezius and the erector spinae muscles. The normalized EMG for the trapezius muscles showed a 14% and 11% reduction in muscle activity at 15° and 30°, respectively, with the advanced design but these positive effects of the advanced design were not found at the greater flexion angles. Likewise the erector spinae muscles showed a 24% and 14% reduction in muscle activity at 15° and 30°, respectively, with the advanced design harness but these effects of the advanced design were not found at the greater forward flexion angles. The level of forward flexion angle affected the rectus abdominis muscle activity, but neither the harness type main effect nor the interaction of harness type and forward flexion angle was significant. The subjective survey results agreed with the EMG results and showed the advanced design harness was generally more comfortable with respect to the shoulder and low back areas. Collectively, the subjective and objective results show a significant improvement with the advanced harness system but also note an interesting interaction with degree of sagittal flexion, indicating a diminished effectiveness of the design improvements at forward flexed postures. Design criteria for harness systems in these forward flexed postures are discussed.

Keywords: Backpack; Electromyography; Awkward postures

1. Introduction

Backpacks are a common form of load carriage, and, as such, researchers have studied the effects of these posteriorly mounted loads on the biomechanical stresses of the spine and low back. Not surprisingly, a significant proportion of this backpack research has been focused on the use of backpacks by military personnel (e.g. Knapik et al., 2004; LaFiandra et al., 2004; Quesada et al., 2000; Holewijn and Lotens, 1992). Often these military application-focused studies evaluate the metabolic cost associated with backpack use as well as their impact on the local muscle fatigue that can develop (Quesada et al., 2000). The use of backpacks in recreational activities such as hiking (e.g. Bloom & Woodhull-McNeal, 1987; Stuempfle et al., 2004) and the use of backpacks by schoolchildren (e.g. Steele et al., 2003; Pascoe et al., 1997) have also received

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some attention in the literature. Much of this work has resulted in specific design recommendations (e.g. optimal height of load in backpack, internal vs. external frame backpack, acceptable loads in backpacks).

Analysis of the underlying biomechanics of backpacks has led to a number of important design changes for the upright user. When a posterior load (e.g. a backpack) is added to human standing in an upright, neutral posture, the center of mass of the system (i.e. backpack, torso, head, arms) is shifted in a posterior direction (Goh et al., 1998). The first design recommendation is with regard to the appropriate location of the center of mass of the load. In the anterior/posterior direction the load should be located as close to the body as possible, thereby minimizing the moment created by the load and in the lateral direction the load should be left–right balanced. In the superior inferior direction the answer is a bit more complicated. With a forward flexion of the torso, the person can shift the center of mass of this system to a more balanced location over the biomechanical fulcrum (spine), thereby reducing the muscle forces required to support the load. If the center of mass of the load is located in a more superior position (i.e. higher along the back), the wearer only has to make a small forward flexion motion to put that center of mass directly over the fulcrum thereby minimizing the required muscle force to support the load. This biomechanical logic holds if the task is relatively static in nature, however, the higher location can create challenges if there are significant dynamics because the inertial moment now has a larger moment arm about the low back.

A second category of design recommendations that has come from the research is that a harness should translate a significant proportion of the load in the backpack directly to the pelvis. By transferring more of the backpack load directly to the pelvis (i.e. by-passing the lumbar region) the muscle forces required to support the load are reduced. LaFiandra and Harman (2003) showed that the use of a hip belt with a framed backpack transfers approximately 30% of the vertical force of the backpack to the hips. A further limitation of backpacks without a strong hip belt is that the pressure exerted on the shoulders by the straps from the backpack itself can be significant. Holewijn (1990) showed that the pressure on the shoulders using a frameless pack with only a 10 kg load was 200 mmHg and reasoned that since the waist is three times less sensitive to skin pressure than the shoulder region (Holewijn and Lotens, 1992) transferring the load to the hips with a hip belt decreases the overall discomfort. Holewijn and Lotens (1992) also noted that a hip belt reduces the shoulder girdle muscle activity required to stabilize the mass.

Lateral stiffness rods are another design feature that has been shown to improve this transfer of load to the pelvis. Reid et al. (2004) suggested adding lateral stiffness rods to the lateral edges of the suspension system of the backpack. Their results showed that these lateral stiffness rods transferred 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. This increase in the extensor moment reduces the need for forward flexion of the torso (Stevenson et al., 2004). Further, these authors noted that 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. To summarize the backpack system design recommendations for the upright user: keep the center of mass of the load close to the body, equally balanced from side to side and high up along the back and use a hip belt and lateral transfer rods to translate the vertical forces directly to the pelvis.

There are occupational instances wherein a worker is wearing a back-mounted load and does not maintain an upright posture and this leads one to question the validity of the design recommendations for this scenario. A good example, and the focus of the current work, is the Self Contained Atmospheric Protective Ensemble (SCAPE) suit worn by some employees of the National Aeronautical Space Administration (NASA). These SCAPE suits are required in areas where fuel and an oxidizer are present and can spontaneously ignite on contact (hypergolic atmospheres). 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) that has a mass of approximately 18.2 kg. This system allows a person to breathe regularly, without the use of a regulator or respiratory device. During a SCAPE operation, the main responsibilities of a SCAPE employee are to fuel the rockets, clean up hazardous chemical spills or leaks, remove hazardous gases, connect thrusters for the auxiliary power units (APUs), and/or load propellants (such as N_2O_4). These tasks often require non-neutral torso postures as well as overhead handwork, all while the worker supports the 18.2 kg ECU through a shoulder-mounted backpack harness. The question raised by this scenario is "Would these workers benefit from the advanced backpack system design recommendations that were developed for the upright user?"

The specific objective of this study was to develop and evaluate a more advanced backpack harness system for supporting the ECU and to evaluate this system in various forward-flexed torso postures. It was hypothesized that the advanced design (a design that uses a load-sharing hip belt and lateral stiffness rods) would reduce the activity of the erector spinae, rectus abdominis, and trapezius muscles as compared to a more basic harness design. It was also hypothesized that the advanced harness would improve overall comfort level, but a particular improvement in the comfort of the shoulder region is expected.

2. Methods

2.1. Participants

There were 15 participants in this experiment (twelve men and three women) ranging in age from 21 to 55 years old. The means and standard deviations of relevant anthropometric characteristics are as follows: stature (178, 9.3 cm), mass (87.1, 20.9 kg), chest circumference (103.0, 11.4 cm), waist circumference (90.9, 14.7 cm), shoulder height—acromion to ground (149.4, 8.3 cm), and waist height—top of iliac crest to ground (107.3, 5.9 cm). None of the participants had any experience in SCAPE operations.

2.2. Apparatus

The external load used in the experiment was a mock-up ECU that was dimensionally accurate in terms of size/shape (57 cm tall $\times$ 46 cm wide $\times$ 23 cm deep), load (18.2 kg) and balance (mass evenly distributed throughout the volume). This load was secured to the backs of the participants using two different harnesses. The first harness (the basic harness) is a harness that is currently used by NASA in the SCAPE suits. In this harness system the load of the ECU is supported primarily by the shoulder straps and to a lesser extent the interaction of the ECU and the surface of the back (friction). The second harness (the advanced harness) was a modification of a commercially available external framed pack (Kelty® Sierra Crest). This harness was chosen because it featured many characteristics found to beneficial in previous studies (a hip belt, load lifter straps, padded shoulder straps, and an adjustable harness for varied torso lengths). The modifications made to this harness were some structural modifications that allowed the ECU to be secured to the frame of the harness and the addition of lateral stiffness rods (Fig. 1). Relative to the spine, the three-dimensional position of the center of mass of the ECU load was the same in both harness designs. This was accomplished by centering the load on the spine, tightening the harness so that the load fit snugly against the back and then adjusting the height of the top of the ECU so that it was at the same height relative to the C7 vertebrae across the two harness types. Due to anthropometric variability in the subject pool, the exact distance of the top of the ECU to the C7 vertebrae varied between subjects, but for a given subject the vertical position of the ECU was constant across harness types.

Surface electromyography was used to assess the intensity of muscle contraction during the experimental trials. Six pairs of bipolar surface Ag–AgCl electrodes (Model E22x, In-vivo Metric, CA, USA) were used to collect the EMG data from the right and left pairs of the erector spinae muscles, rectus abdominis muscles, and upper trapezius (pars descendens) muscles. These data were pre-amplified ($1000\times$) and then carried via shielded cable to main amplifiers that filtered (60 Hz, and low pass 1000 Hz) and further amplified ($50\times$) the EMG data (EMG system custom built by Data Design, Columbus OH). All EMG data were collected at 1024 Hz.

2.3. Experimental procedure

Upon arrival, the subject's anthropometric measurements were taken and then they were introduced to the

Fig. 1. The side view of the ECU and the advanced harness system.

procedures and equipment used for this experiment. The six pairs of surface electrodes were placed according to Mirka and Marras (1993) (for the erector spinae and rectus abdominis muscles) and Leyman et al. (2004) (for the upper trapezius (pars descendens) muscles). These EMG data were collected at 1024 Hz. After the surface electrodes were placed and signal quality verified, the participant performed posture-specific maximum voluntary contractions (MVC) for each muscle group following the procedures of Lutz et al. (2001) (for the upper trapezius (pars descendens)) and Mirka and Marras, 1993 (for the erector spinae and rectus abdominis muscles).

Upon completion of the MVCs, the subject donned either the basic harness or the advanced harness. The participant then performed the randomized sequence of forward flexion angles. They began by crossing their arms across their chest and then gradually bending forward until they reached the designated angle (as established with a bubble-leveled goniometer). Once the participant reached the required flexion angle, the muscle activity data for all muscles were collected for 3 s.

After completing all of the trials for one harness, the harness was removed, and the subject completed a post-test subjective survey for that particular harness. The post-test survey asked each subject to rate (on a five point Likert scale: 1—no discomfort, 5—very uncomfortable) the following four categories for each harness: the discomfort level of the (1) skin on the shoulders, (2) trapezius muscles, (3) low back muscles, and (4) overall comfort of the harness. In these subjective surveys, the basic harness was described as the green harness and the advanced harness the black harness to avoid experimenter-induced bias in the responses. 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.

After the survey was answered, the subject was given a 5 min break before the other harness was donned. After completing the trials with the second harness, the subject completed the post-test survey for that particular harness and also completed the final comparison survey. The final comparison survey asked the participants to compare (1—much worse, 5—much better) the two harnesses in three areas: overall comfort, comfort level while standing upright, and the comfort level while leaning forward in the 60° angle. For example, one question read: "With regard to overall comfort, how would you rate the green harness to the black harness?"

2.4. Experimental design

There were two independent variables in this study. The first independent variable was harness type with two levels: the "basic" harness and the "advanced" harness. The second independent variable was the forward flexion angle with four levels: 15°, 30°, 45°, and 60°. Each subject was exposed to all combinations of harness and forward flexion angle. Each combination of independent variables was performed two times. There was a restriction on complete randomization in that the participants wore one harness system and completed all forward flexion angles and then changed to the other system and completed all of the flexion angles. The flexion angles were completely randomized within each harness type level and the presentation order of harness type was counterbalanced across subjects.

There were 10 dependent measures 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 abdominis, and trapezius muscles. The task being sagittaly symmetric, the left and right sides of each muscle group were averaged together to obtain one measure of each muscle group. The remaining dependent variables were subjective evaluations by the participant of harness system comfort level.

2.5. Data processing

While there was no further processing of the subjective data required, the EMG data were normalized with respect to the MVC values for each muscle and then averaged. The first step in the EMG normalization process was to establish the MVC EMG value for each muscle in each forward flexion posture according to the procedure described in Jiang et al. (2005). Next, the 3 s of trial data were averaged and then normalized relative to this posture-specific MVC EMG value.

2.6. Statistical analysis

Since the experimental trials were not completely randomized, a split-plot design model was used for the statistical analysis of the normalized EMG data. For the EMG data, ANOVA was used to evaluate the effects of the independent variables (and their interaction) on these dependent measures. For effects that were found to be significant, the Tukey–Kramer honestly significant difference (HSD) post-hoc test was performed to further clarify this effect. 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. For the survey responses, a non-parametric one-way ANOVA (Kruskal–Wallis test) was used for the analysis. A Bonferroni-corrected 0.05 level (to control for experiment-wise error rate) was used as the criterion for significance in all statistical tests.

3. Results

The results of the analysis of the normalized EMG showed an interesting interaction between harness type and flexion angle for both the erector spinae ($F = 5.14$; $p = 0.0019$) and the trapezius muscles ($F = 3.52$; $p = 0.0161$) (Figs. 2 and 3), but this interaction was not significant for the rectus abdominis. Follow-up simple effects analysis revealed a significant main effect of flexion angle for the erector spinae ($F = 204.8$; $p < 0.0001$) and the rectus abdominis ($F = 16.49$; $p < 0.0001$). The results of this simple effects analysis reveals that the effects of harness type are found only in their interaction with flexion angle.

An emphasis is placed here on the results of the forward flexion angles of 15° and 30° as these represent the angles most commonly assumed during SCAPE operations. For the trapezius muscles at 15° and 30°, the advanced harness had a 14% and 11% reduction, respectively, in muscle activity compared to the basic harness. For the erector spinae muscles at 15° and 30°, the advanced harness had a 24% and 14% reduction, respectively, in muscle activity compared to the basic harness.

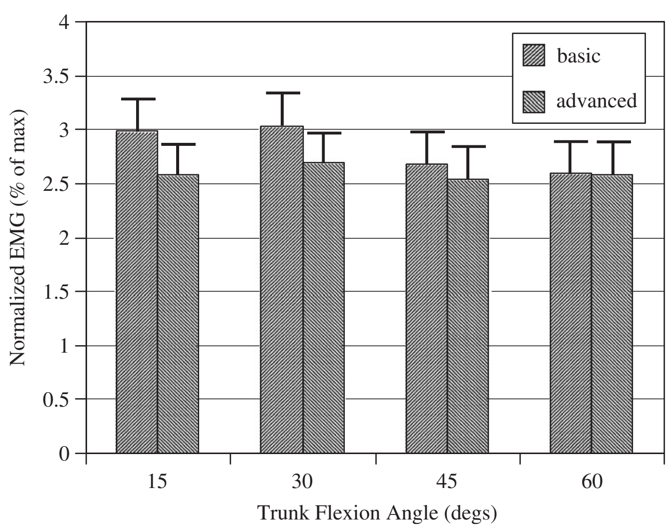

Fig. 2. Normalized EMG of the trapezius muscles as a function of harness type and forward flexion angle.

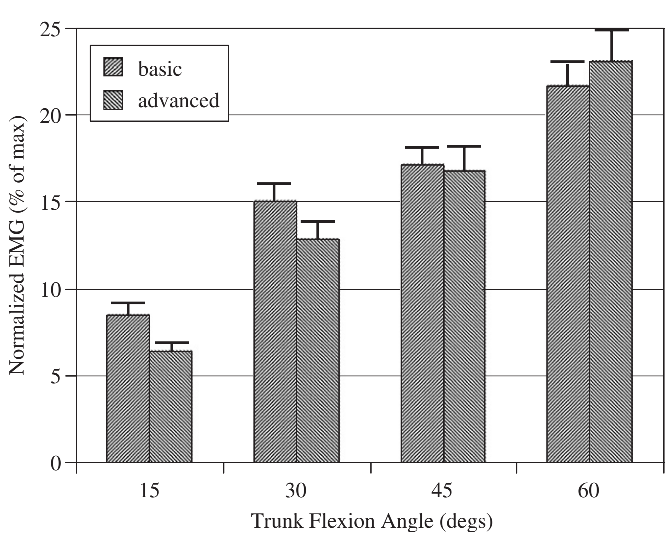

Fig. 3. Normalized EMG of the erector spinae muscles as a function of harness type and forward flexion.

The results of the analysis of the subjective data showed a significant effect of harness type for all questions (shoulder skin: $\chi^2 = 18.6$; $p < 0.0001$, trapezius muscles: $\chi^2 = 15.3132$; $p < 0.0001$, low back muscles: $\chi^2 = 14.4515$; $p < 0.0001$; overall: $\chi^2 = 15.8572$; $p < 0.0001$) (Fig. 4). In the final comparison survey the basic harness was consistently rated "somewhat worse" than the advanced harness (Overall rating: 2.0, Upright support rating: 1.95 and Flexed Support rating: 2.1). The procedures for the collection of these subjective ratings did not allow for an evaluation of the interaction between harness type and flexion angle (as was shown in the EMG data) but does provide data indicating increased comfort with the advanced harness design.

4. Discussion

The results of this study point to an interesting interaction that gets to the very core of the question regarding the effectiveness of current backpack design recommendations in non-neutral trunk postures. The results of this study have shown that there is a diminishing positive biomechanical effect of the advanced design strategies (hip belt and lateral stiffness bars) as the trunk flexion angle increases. This is due in part to the fact that while leaning over into more flexed postures, more of the weight of the ECU is focused on the mid to low back and not as much on the shoulders, thus explaining why there is a reduction in the muscle activity of the trapezius muscles as the forward flexion angle increases.

The results of this study have provided some clear direction for the specific application (SCAPE work) under study. First, the results of this study have demonstrated a

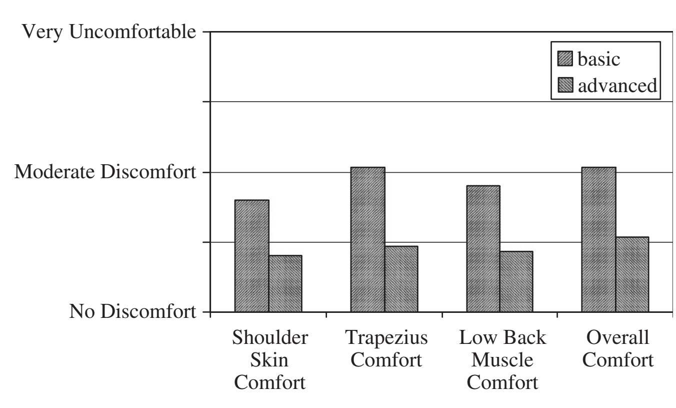

Fig. 4. Subjective assessment of comfort by harness type.

positive effect of the advanced harness system in postures less than 45°, which are common postures that SCAPE workers find themselves in most of the workday. It is also clear that while the positive effects of these improvements are lost at greater flexion angles, the results of this work indicate that there is no detrimental effect of the advanced harness system at these angles. Second, while vertical position of the center of mass of the load was not specifically tested as an independent variable in the current study, it is clear that the general recommendation for high positioning of the center of mass of a load in more upright posture (e.g. Stuempfle et al., 2004) is not recommended in the kinds of postures considered in the current study. In reviewing the strong impact that flexion angle had on the muscle activation levels (particularly the erector spinae) it is clear that a lower positioning of the center of mass of the backpack is appropriate. While this might require a more severe flexed posture to maintain balance during more upright activities (and greater activation of the trunk flexor muscle groups), the cost of a significant load with a long moment arm about the L5/S1 intervertebral joint is clearly an important consideration. Ideally, the ergonomist faced with this challenge will consider the relative proportion of time spent in the various levels of trunk flexion and make an appropriate recommendation to balance these costs.

An important issue that was not addressed in the current study was the use of the upper extremity when wearing the backpack systems. In the current study the participants were asked to cross their arms across their chests during the isometric trials. In more realistic SCAPE operations the workers are often using their arms for various activities that require a variety of upper extremity postures. If the harness system that the workers are using does not reduce or eliminate the force of the shoulder straps on the shoulder, as the worker raises his/her arms to perform the task, he/she must lift some of all of the weight of the ECU in a shrugging motion, thereby increasing muscle load and fatigue potential. A harness system that can take the load off of the shoulders will help reduce this effect regardless of trunk flexion angle.

There are a number of limitations to the current study that may limit, somewhat, the generalizability of these results. First, the task performed in this experiment was isometric posture holding. In more realistic occupational scenarios, the dynamics of the backpack load should be considered. This consideration further emphasizes the point made earlier that the center of mass of the load should be located lower on the back to reduce the moment arm of the inertial load, as noted by Holewijn and Lotens (1992). It is possible that dynamic activities could have shown even more significant differences between harness types or impacted the perception of the comfort level of each harness. The second limitation is the short duration that the subject wore each harness type. Recall that the subjective responses regarding the comfort level of each harness were 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 h based on such a short period of exposure to the both harnesses. 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 s (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 2 h, just like they do a typical SCAPE operation, this may impact the perception of the comfort level of each harness.

5. Conclusions

Much of the research on backpack design has been focused on spinal loading/biomechanics while the wearer is in a neutral/upright trunk posture. The specific objective of this study was to evaluate the effects of trunk flexion angle on the effectiveness of the design recommendations that have been put forward for these more upright postures. The EMG results showed the advancements put forward for these upright postures had diminishing effects as the individual flexes beyond 30°. The advanced harness design reduced the activity of trapezius and erector spinae muscles at 15° by 14% and 24%, respectively, and at 30° by 11% and 14%, respectively, but did not show an effect at either 45° or 60°. The subjective responses of the participants supported the objective EMG data. The results of this study have answered specific questions with regard to the utility of more advanced backpack harness system design in SCAPE operations, but have also provided some insight into the general questions related to backpack use in forward flexed postures.

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