Ergonomic Research on Manufacturing Tasks

Interim Report

Ford Motor Company, The Boeing Company, and Equipois, Inc.

Submitted by:

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Executive Summary

Forthcoming

1. Introduction

Two studies were completed with one overarching goal, that being to complete an initial investigation of the efficacy of using an assistive device (AD). This device is intended for use for tasks requiring elevated arm postures, specifically to “offload” the shoulder muscles. Since upper-extremity loads are transferred largely to the low back, as external moments, it was of interest initially (Phase I) to determine whether such low back loads would be tolerable, and over what range. Secondary goals of the first study were to: 1) determine if this tolerance differs between AD designs (i.e., rigid front vs. rigid back); 2) assess the effects of wearing the AD on postural control; and 3) to obtain preliminary usability results regarding the AD. Prior to more detailed investigations of the benefits of the AD and/or usability studies, this initial study was conducted to determine if the noted thresholds include levels of low back load that are within a range expected with foreseeable use. In other words, if tolerable low back loads are excessively low in the current AD design configuration, further testing is not well justified. These goals were achieved using a combination of subjective (perceived discomfort) and objective (low-back kinematics and kinetics, and balance) measures.

The second study (Phase II) had a primary goal of evaluating the “tradeoff” between upper extremity and low-back loads, respectively involved when using either manual or assisted methods (the latter using the AD). An experiment was conducted that simulated overhead work using different tools (varying masses). Comparisons between manual and assisted methods were made based on perceived discomfort and level of muscle activity in multiple body regions.

2. Phase I: Low-back Moment Tolerance

2.1. Methods

2.1.1. Participants and Experimental Procedures

Twelve healthy individuals (9M, 3F) with no self-reported history of musculoskeletal disorders completed the study, and were recruited from the local community. Respective mean (SD) values of age, stature, and body mass were 24 (3.1) yrs, 173 (9.6) cm, and 74 (11.9) kg. Participants completed informed consent procedures approved by the Virginia Tech Institutional Review Board prior to their participation in the study.

In this study, low back loads were operationalized based on external moments induced by the AD. Specifically, responses to induced moments at the lumbosacral joint (L5/S1) were of interest, due to gravitational (and later, perhaps, inertial) loads applied by/on the AD. To remove a number of potential modifying factors and influences, external L5/S1 moments were applied using a custom fixture. Note that low back loads can be conceptualized using different measures, such as the internal loads on the spine (e.g., compression and shear forces). However, moment loads at the low back are likely perceivable, and it is also likely that these moments are used when an individual determines perceived levels of “safe” loading (i.e., psychophysical limits) and/or responses regarding discomfort levels. Furthermore, low back moments are likely to be closely related to the rate of fatigue onset and/or endurance times. In contrast, there is no evidence (of which we are aware) to suggest that internal spine loads are perceived except in extreme cases.

Each participant completed 12 trials of intermittent low back moment loading under all combinations of two vests (**B = rigid front** and **C = rigid back**), three external payloads (**2.5, 10 and 17.5 lbs**), and two duty cycles (**25% vs. 50%**). The latter two independent variables, and the specific levels of each, were selected by the sponsor to be representative of intended and/or expected conditions of use. In each condition, six cycles were completed, with a cycle time = 2 min. As such, each trial lasted 12 minutes, and involved either three or six minutes of "work" in the respective duty cycle conditions. A 2-minute rest break was given between each trial, and the order of exposure to the conditions was counterbalanced using a Latin Square. Computer-generated auditory tones were used to control pacing (i.e., the start and end of each work and rest period). Prior to completing the main session involving the 12 conditions, all participants completed a preliminary session in which they were familiarized with the procedures and conditions and were provided extensive practice.

In the both the preliminary and main sessions, participants completed a procedure to "calibrate" them at providing rating of perceived discomfort (RPD). Such ratings were obtained during the experiment using Borg's CR-10 scale (Borg 1990). In this calibration, participants leaned against a wall with their knees bent 90 degrees (Figure 1). They provided RPDs intermittently, until reporting a value of ≥9 (i.e., nearly maximal or maximal discomfort). In the main experiment, and after initial preparation and warm up, participants stood with each foot on a separate force platform (AMTI OR6-7-1000; AMTI, Watertown, MA, USA), and were asked to find comfortable positions of their foot (or stance). These positions were marked on the force platforms.

Figure 1. Participant completing a calibration trial for reporting perceived discomfort.

Before donning the vest¸ participants completed three trials of upright stance to measure baseline balance (operationalized here based on postural sway). Participants stood on the force platforms for 60 seconds in each trial, with their feet in predefined positions (marked, as described earlier), and were instructed to gaze forward. These stance trials also facilitated associating the locations of marker clusters on the participants' pelvis with four single markers placed on pelvic bony landmarks (i.e., anterior and posterior iliac superior spines). After the balance tests, these four single markers were removed and participants donned the vest. A 10 lb payload was applied to adjust the "balance" of the fixture. Subsequently, participants performed another three stance trials with the fixture in a "home" position and with no payload.

Rest and work periods of each cycle involved changing the configuration of a fixture (segmented arm) that was attached to the vest. This configuration alternated between "home" and "extended" positions, respectively. In the home position (Figure 2) a nominal level of external low back moment was applied. In the latter, the fixture was extended so the distal portion was aligned anterior to the participants' right shoulder joint. This specific location and orientation, resulting in mainly external torso flexion moments with some lateral bending, was used to simulate moments that would result from using a tool during overhead work. During the experiment, the extended position was maintained by one of the experimenters during the working periods (Figure 2). RPDs were obtained, for the low back region, immediately after completing the working portion of each cycle. Participants were allowed to move freely with the fixture arm in the home position during the rest portion of each cycle, but were asked to keep each foot in the marked area on the force platform during the work portions. External masses were applied to the fixture (Figure 2) in a consistent location, such that the moment arm was the same as it would be when using the Equipois arm in an extended configuration. After completing each condition, and again after completing all 12, participants were asked to provide feedback regarding vest fit, usability, and any other suggestions related to the vest(s).

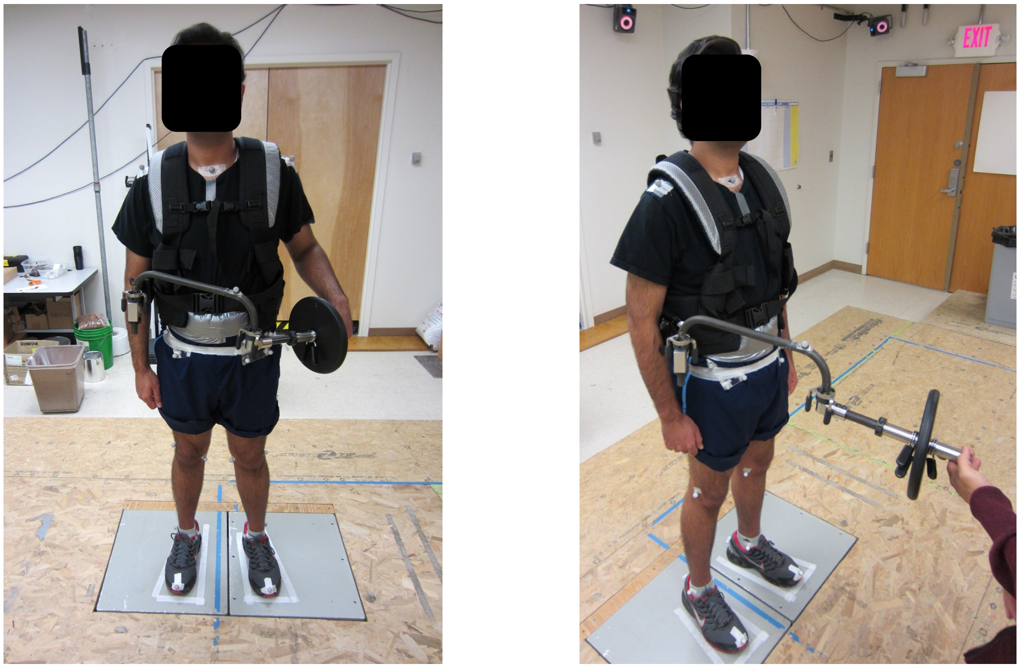


Figure 2. Experimental configuration during the home (left) and extended (right) positions, respectively corresponding to the resting and working portions of each cycle. In the working portion, participants kept each foot in a pre-marked area on separate force platforms and the fixture arm was maintained at a consistent angle in the horizontal plane.

2.1.2. Instrumentation

Tri-axial ground reaction forces and moments were recorded during each trial from the two force platforms, with a sampling frequency of 960 Hz. These signals were subsequently low-pass filtered (15 Hz cut-off; 2nd order Butterworth; bidirectional). Body positions were monitored using passive reflective markers. Marker data were collected at 60 Hz using a seven-camera system (Vicon MX-T10; Vicon System, LA, USA) and low-pass filtered (10 Hz cut-off; 2nd order Butterworth; bidirectional). Markers were placed bilaterally or centrally over the following anatomical landmarks: calcaneus; second metatarsal head; lateral and medial malleoli; lateral and medial tibial epicondyles; acromial processes; spinous processes of the seventh cervical (C7); incisura jugularis; and anterior and posterior iliac superior spines. In addition, clusters of two and three markers were placed bilaterally over the pelvis and great trochanters. Before the participant donned the vest, selected markers on the pelvis were removed, as noted earlier, after being referenced to the corresponding cluster. Removed markers were reconstructed using the cluster on the corresponding body segments (Veldpaus, Woltring et al. 1988). A joint coordinate system for each segment was defined, largely based on International Society of Biomechanics recommendations (Wu and Cavanagh 1995; Wu, Siegler et al. 2002). All off-line data processing was completed using Matlab 7 (Mathworks™ Inc., Natick, MA, USA).

2.2.3 Outcome Measures and Statistical Analysis

For each trial, several objective and subjective outcome measures (i.e. dependent variables) were obtained. Objective measures were: three-dimensional external moments about the lumbosacral (L5/S1) joint, trunk angles relative to the pelvis, and center-of-pressure (COP)-based balance measures (i.e., mean COP velocity). Mean COP velocity was obtained separately in the antero-posterior (AP) and medial-lateral (ML) directions, as defined in Prieto et al. (1996). RPDs, obtained using the Borg CR-10 scale, were available at the end of each cycle within each trial. Only the final RPD values (after six cycles, or 12 minutes) were formally (statistically) analyzed.

Separate repeated-measures analyses of variance (RANOVA) were used to assess the effects of vest, payload, and duty cycle on each of the outcome measures. Where relevant, *post hoc* paired comparisons were performed using Tukey's HSD. Statistical analyses were conducted using JMP 9.0 (SAS Institute Inc., Cary, NC, USA), and significance was determined when $p < 0.05$. All summary data are presented as means (SD).

2.2. Results

2.2.1. Ratings of Perceived Discomfort

In all conditions, RPDs increased (from 0) at the first measurements that were taken following the first 2-minute cycle (Figure 3). Again in all conditions, RPDs increased over time, though several appeared to reach plateaus by the 5th or 6th cycle (i.e., after 10-12 minutes). Qualitatively, there were no differences in RPDs over time for the two vests. However, both heavier payloads and the higher duty cycle led to larger RPDs and more rapid increases over time. An interaction effect of payload x duty cycle was also evident, with the effects of duty cycle being more substantial with higher payloads (and vice versa). One notable exception was present, in that an opposite effect of duty cycle was found using Vest B with the 10 lb payload; specific reasons for this are not clear, and this contrary outcome was only present among only a few participants.

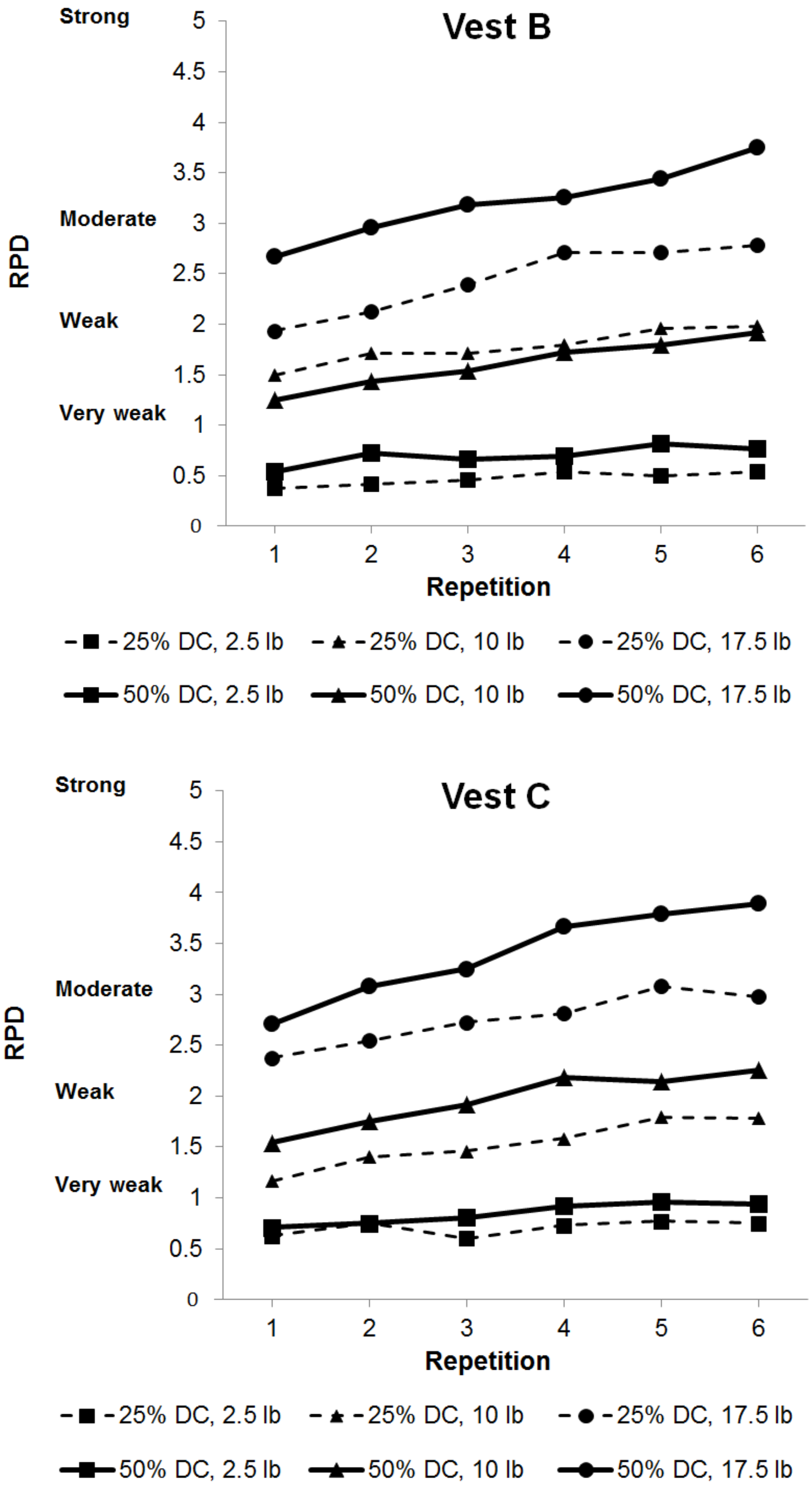


Figure 3. Mean ratings of perceived discomfort (RPDs) in the low back when using vests B (rigid front) and C (rigid back) in all combinations of payload and duty cycle. Note: each repetition is a two-minute cycle.

Statistical effects of vest, payload, and duty cycle on final RPD values are summarized in Table 1. Both the main effects of payload and duty cycle and their interaction were significant. Final RPDs increased substantially, and significantly, with payload and in the higher duty cycle (Figure 4). The effect of the higher duty cycle was most evident when using the heaviest payload (Figure 4).

Table 1. RANOVA results [*F* value and (*p* value)] for the effects of vest (V), payload (P), and duty cycle (DC) on final low-back RPDs. Significant effects are highlighted using bolded text.

	Vest	**Payload**	**Duty Cycle**	**VxP**	**VxDC**	**PxDC**	**VxPxDC**
RPD	3.8 (**0.077**)	46.9 (**<0.0001**)	4.74 (**0.034**)	0.10 (0.90)	0.28 (0.60)	72.0 (**<0.0001**)	0.03 (0.97)
Torso Angle	to	be	completed				
L5/S1 Moment							
Mean COP Vel.							

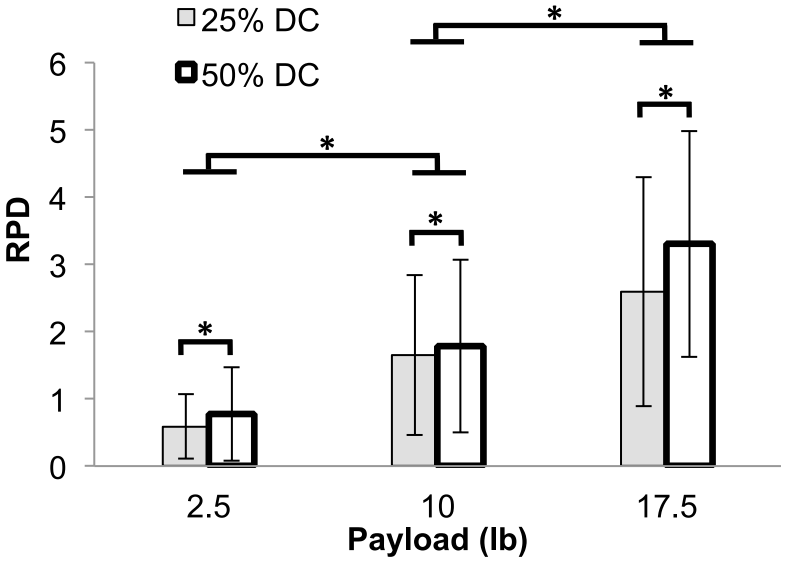


Figure 4. Mean values of final low-back RPDs for all combinations of payload and duty cycle (DC). The symbol * indicates a significant pairwise difference between payload conditions and differences in response to the two duty cycles within a given payload.

2.2.2. Participant Feedback

Some of the participants indicated that the rigid front vest (vest B) was a better tool regarding load carriage. For this same vest, however, they indicated some drawbacks for this vest such as feeling pressure on the chest, discomfort in the upper back (including the shoulders) and neck, and unbalanced pressure on the shoulders and low back. On the other hand, some participants indicated that the rigid back vest (vest C) was more comfortable, particularly with light payloads, and that while the rigid back vest distributed the load better it also provided less support with heavy loads.

3. Phase II: Effects of Using the Exo Vest

3.1. Methods

3.1.1. Participants, Experimental Design, and Procedures

Twelve healthy males with no self-reported history of musculoskeletal disorders completed the study, and were recruited from the local community. While females were not excluded, only a few volunteered, and none were found to be able to complete the most demanding of the experimental conditions involved (see below). Respective mean (SD) values of participant age, stature, and body mass were 27 (2.6) yrs, 178 (4.6) cm, and 76 (4.6) kg. Each participant completed informed consent procedures approved by the Virginia Tech Institutional Review Board prior to any data collections.

Participants performed a simulation of intermittent, repetitive overhead work, in each of six different experimental conditions. These conditions were based on discussions with the sponsor, and intended as representative of expected future use of the AD. There were two vest conditions ("with vest" vs. "no vest") and three payloads (tool masses = 1.1, 3.4 and 8.1 kg). The Exo vest was used with the Equipois zeroG2 arm (Figure 5). The two heavier tools were provided by the sponsor, while the lightest was constructed by Virginia Tech (Figure 6). Note that the three tools were configured for "right-angled" use, and attachments were included such that the distance from the hand to the end-effector (hex-head driver) was consistent across tools.

Figure 5. Equipois zeroG2 arm (left) and Exo vest (right).

Figure 6. Three hand tool differing in mass (1.1, 3.4, and 8.1 kg, from left to right).

An overhead task was simulated, and which involved using the tool to engage a hex-head bolt in an inverted orientation. During the simulated work, participants maintained light contact of the driver on the bold by using both hands (Figure 7), with the right hand under the driver. Based on discussion with the sponsor, the target height was set for each participant, such that the hands were “slightly above head height”. This was achieved using an adjustable fixture (Figure 7), which was located such that the center of the left wrist (wrist crease) was at a height equal to participant stature.

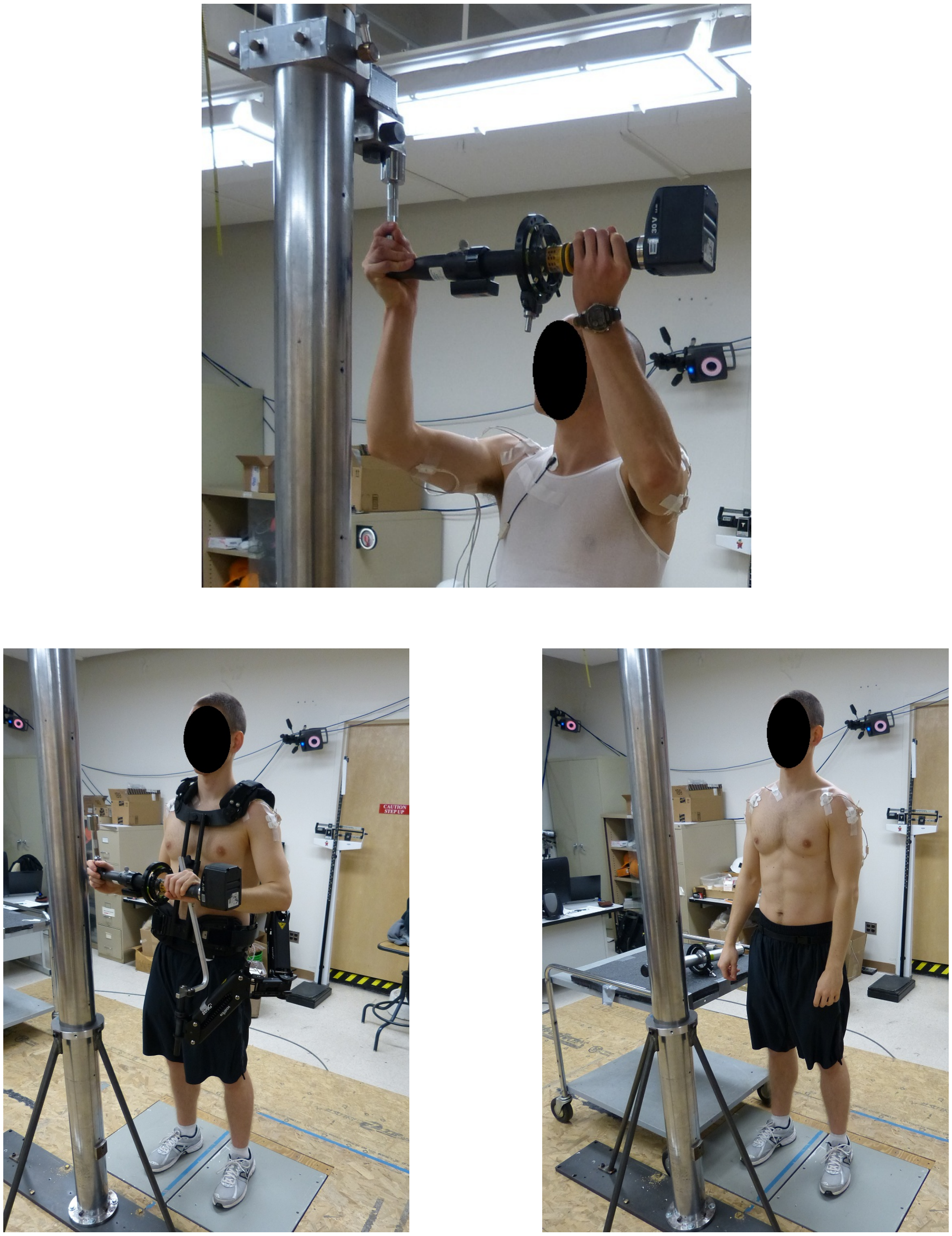


Figure 7. Postures during the work portion of each cycle (Top), and during the rest portion of each cycle [Bottom Left – with vest; Bottom Right – no vest).

In each of the six conditions, and as determined by the sponsor, participants repeated the overhead task with a 50% duty cycle and 30 sec. cycle time (i.e., 15 sec. work and 15 sec. rest). This was repeated for 10 minutes (i.e., 20 cycles) in each condition, and using computer-generated auditory tones to indicate the start/end of each work and rest period. During the “rest” portion of each cycle, participants adopted either a specified posture when using the vest or placed the tool on a table in the no vest condition (Figure 7). The latter presumed that in actual application the tool would not be supported between instances of use (e.g., a tool balancer would be used). The presentation order of vest conditions was counterbalanced, and within each vest condition the three hand tool masses were presented in a counterbalanced order using a Latin square. Between conditions, participants were given a minimum of 5 min. rest to minimize potential fatigue effects.

Participants completed a preliminary session and one data collection session. Upon arrival for both sessions, participants were first asked to perform warm up exercises for the shoulders and the trunk, and then were calibrated, as described in Phase I, with a 10-point modified Borg CR-10 scale to report ratings of perceived discomfort (RPD). In the preliminary session, participants practiced for ~ 1 hr to become familiarized with each of the experimental conditions.

In the data collection session, bilateral muscle activity of four muscle groups was monitored: triceps brachii (upper arm), anterior and middle deltoid (shoulder), and iliocostalis lumborum pars lumborum (low back). For this, pairs of bipolar Ag/AgCl electrodes (AccuSensor, Lynn Medical, MI) with a 2.5 cm inter-electrode distance were placed on the skin surface, according to standard procedures (Hermens, Freriks et al. 1999). Before performing the overhead task, muscle activity was captured for 15 sec. while participants simulated the overhead task without a hand tool (Figure 8). This task served as a "reference contraction", and EMGs from it were used to normalize values obtained during the subsequent tasks. Participants then performed 20 cycles of the overhead task under each of experimental conditions. In each, participants provided RPD values for the upper arm, shoulder, and low back right after every four cycles (i.e., every 2 min.). Participants were asked to provide a composite RPD value, representing overall perceptions across the left and right sides. These three body regions were selected from initial pilot results, and the order of body region solicited was varied randomly during each trial.

Figure 8. Reference contraction posture, during which EMG measures were obtained for purposes of normalization.

During the simulated work, participants self-selected their postures and were allowed to change their foot positions as desired. However, foot placements were restricted to being on separate force platforms (AMTI OR6-7-1000; AMTI, Watertown, MA, USA). In the vest condition, participants were fitted with the Exo vest, according to the recommended procedure by the manufacturer (Equipois® Inc.), and the stiffness of the zeroG2 arm springs was adjusted so that the hand tool mass was located at the height of the participants' neck. After completing all experimental conditions, participants were asked to comment on the vest (e.g., fit and usability).

3.1.2. Instrumentation

Raw EMG signals were collected using two telemetered systems (TeleMyo 900, Noraxon, AZ, USA), sampled at 960 Hz, band-pass filtered (20-400 Hz), rectified, low-pass filtered at 5 Hz (bidirectional 2nd-order Butterworth) and normalized using individual minimal values from the reference contractions. The first 3 and last 2 seconds of each working cycle were removed to reduce transition effects, and then mean values were obtained as dependent measures.

Tri-axial ground reaction forces and moments were recorded during each trial from the two force platforms, with a sampling frequency of 960 Hz. These signals were subsequently low-pass filtered (15 Hz cut-off; 2nd order Butterworth; bidirectional), and served to ensure that only marginal forces were obtained on the fixture. Location (height from floor) of the hand tools was monitored using one passive reflective marker, and this served to identify work and rest periods. Marker data were collected at 60 Hz using a seven-camera system (Vicon MX-T10; Vicon System, LA, USA) and low-pass filtered (10 Hz cut-off; 2nd order Butterworth; bidirectional). All off-line data processing was completed using Matlab 7 (Mathworks™ Inc., Natick, MA, USA).

3.1.3 Statistical Analyses

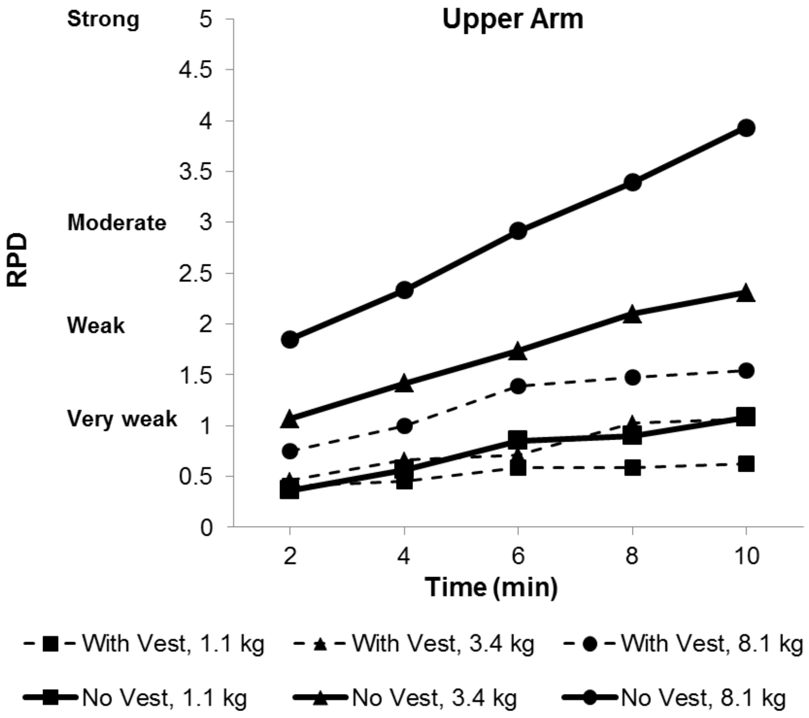
RPDs, from the upper arm, shoulder, and low back, were available at 2-min intervals during trials. Only the final RPD values (after 20 cycles, or 10 minutes) were formally (statistically) analyzed. Normalized EMGs (nEMG), from the upper arm, shoulder, and low back, were available from the working portion of each cycle.

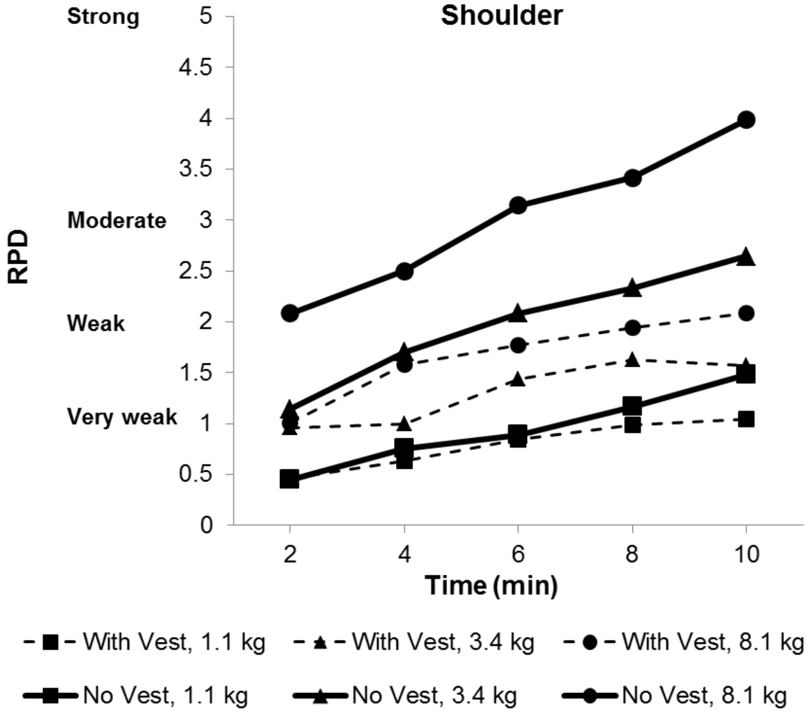
Separate repeated-measures analyses of variance (RANOVA) were used to assess the effects of vest and payload on RPDs and nEMGs. Where relevant, *post hoc* pairwise comparisons were performed using Tukey's HSD. All statistical analyses were conducted using JMP 9.0 (SAS Institute Inc., Cary, NC, USA), and statistical significance was determined when $p < 0.05$. All summary data are presented as means (SD).

3.2. Results

3.2.1. Ratings of Perceived Discomfort

For all three body regions, RPDs increased over time in all of the vest and payload conditions (Figure 9). For the upper arm and shoulder, RPDs appear to reach plateaus when using the vest, but continued to increase without the vest. Linear increases were evident at the low back across all conditions. For a given payload level, RPDs of the upper arm and shoulder were substantially lower throughout the trial duration when using the vest. In contrast, low-back RPDs were higher throughout the trial duration when using the vest, though this effect seemed smaller in comparison to the results for the upper extremity.


Upper Arm
RPD
Strong
Moderate
Weak
Very weak
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
2
4
6
8
10
Time (min)
With Vest, 1.1 kg
With Vest, 3.4 kg
With Vest, 8.1 kg
No Vest, 1.1 kg
No Vest, 3.4 kg
No Vest, 8.1 kg


Shoulder
RPD
Strong
Moderate
Weak
Very weak
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
2
4
6
8
10
Time (min)
With Vest, 1.1 kg
With Vest, 3.4 kg
With Vest, 8.1 kg
No Vest, 1.1 kg
No Vest, 3.4 kg
No Vest, 8.1 kg

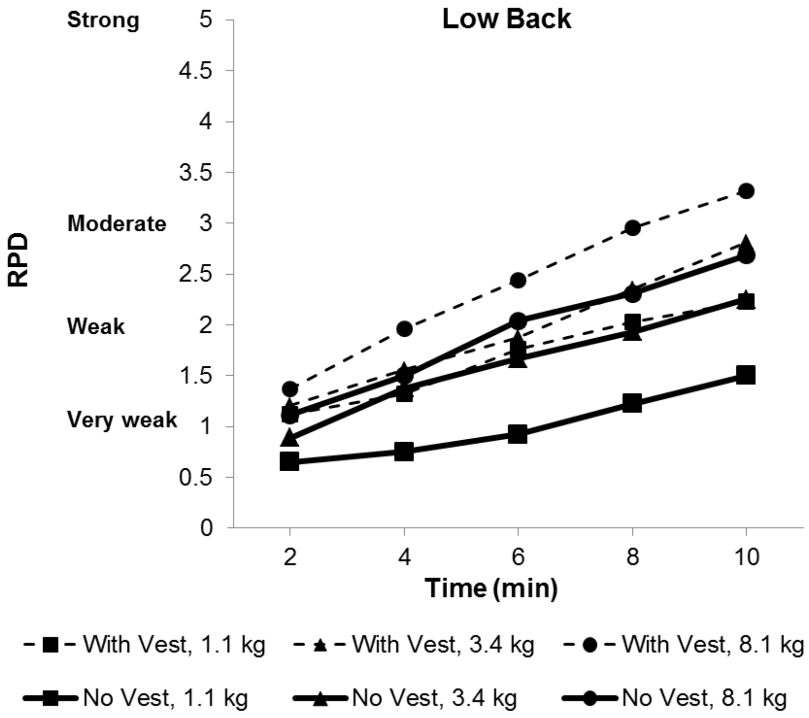
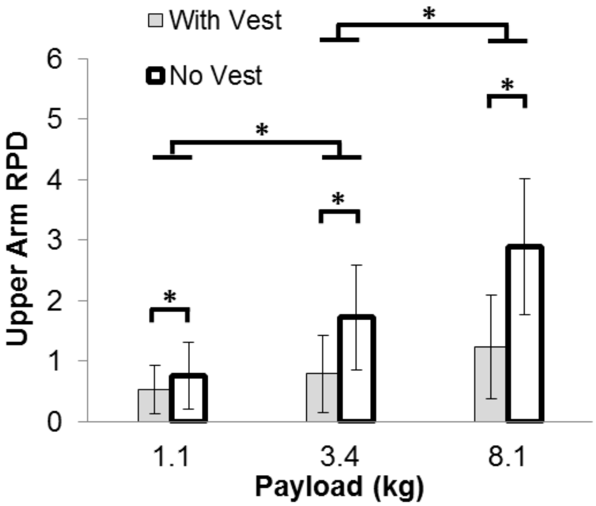


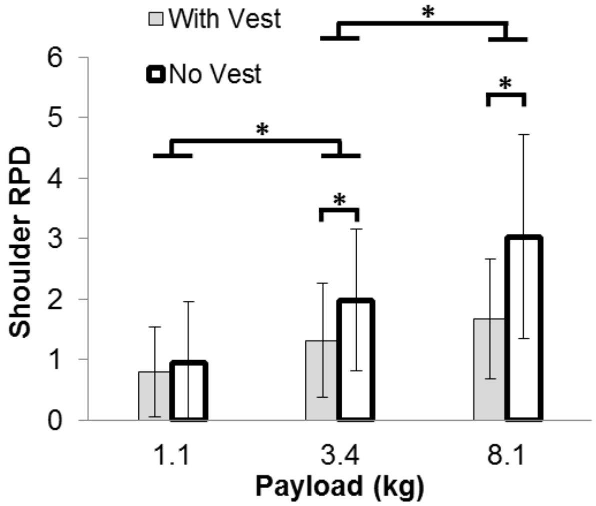
Figure 9. Mean ratings of perceived discomfort (RPDs) for upper arm (top), shoulder (middle), and low back (bottom) in all combinations of vest condition and payload.

A summary of RANOVA results for the effects of vest and payload on the final PRD values is presented in Table 2 for each body region. Significant main effects of vest and payload were found on RPD values for the upper arm and shoulder. In both cases, RPD increased with payload and were smaller when using the vest. For the upper arm, there was a significant payload x vest interaction effect, and the decrease with vest use was more substantial when using heavier payloads (Figure 10). A similar interactive effect was evident for the shoulder, though this was not significant. For the low back, RPDs also increased with payload, though the magnitude of this effect was smaller than for the upper extremity. The effect of vest approached significance, with higher values reported when the vest was used.

Table 2. RANOVA results [*F* value (*p* value)] for effects of payload and vest condition on final RPD values for the upper arm, shoulder, and low back. Significant effects are indicated by bolded text.

	Payload	**Vest**	**Payload x Vest**
Upper Arm	45.1 (**<0.0001**)	74.3 (**<0.0001**)	5.6 (**0.0062**)
Shoulder	24.4 (**<0.0001**)	26.1 (**<0.0001**)	1.7 (0.20)
Low Back	6.08 (**0.0043**)	3.22 (0.079)	0.35 (0.71)


With Vest
No Vest
Upper Arm RPD
0
1
2
3
4
5
6
*
*
*
*
*
*
1.1
3.4
8.1
Payload (kg)


With Vest
No Vest
Shoulder RPD
0
1
2
3
4
5
6
*
*
*
*
*
1.1
3.4
8.1
Payload (kg)

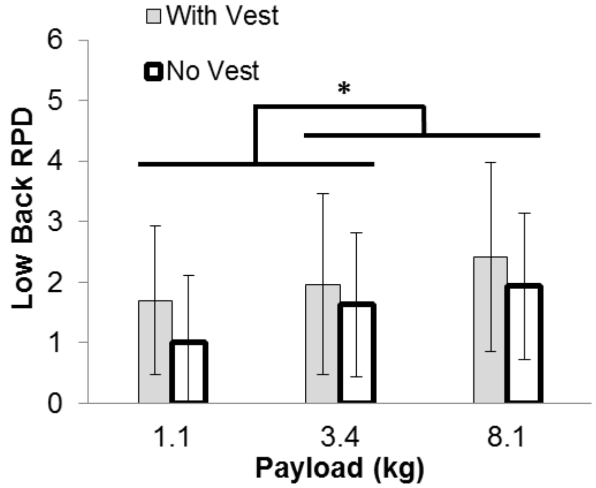

With Vest
No Vest
Low Back RPD
0
1
2
3
4
5
6
*
1.1
3.4
8.1
Payload (kg)

Figure 10. Mean values of final RPDs for all combinations of payload and vest condition. The symbol * indicates a significant pairwise difference between payload conditions and differences between vest conditions within a given payload.

3.2.2. Participant Feedback

Many participants indicated that they preferred using the vest only for the heaviest payload (8.4 kg). Some felt that using the vest would decrease their mobility and preferred not to use it for lighter loads. They commented that the vest restricted their trunk movements, such that they could not move to relieve discomfort by, for example, curving the back. Some participants complained about poor fit in the shoulder straps. Although they initially felt having good shoulder contact with the vest, the shoulder straps were observed to not maintain good contact after a few cycles of the overhead task, and this seemed to lead to more perceived load on the back. Some participants further mentioned that a compromised shoulder fit seemed to cause the vest to become unbalanced (i.e., tilted in the direction of the zeroG2 arm attachment), and that this resulted in the higher low-back RPDs provided. It should also be noted that some participants mentioned that the shoulder straps compromised their performance during the overhead tasks, and they would have preferred to have narrower straps on the Exo vest for this purpose. To prevent such compromised shoulder fit, a tighter fit for the pelvis pads was tested, however many participants complained and asked for a looser fit around the pelvis. Overall, participants preferred to use the vest, especially for the heaviest payload. When asked to choose between using the vest and not using it for all of the conditions, the vast majority said they would choose to use the vest.

4. Discussion and Conclusions

The first experiment simulated what is likely a relatively “extreme” situation, in that the payload was maintained relatively far from the body, thereby inducing relatively large external moments at the low back. Perceptual responses, specifically ratings of perceived low-back discomfort, were generally consistent, and increased with respect to time, duty cycle, and payload. Regarding the changes over time (see Figure 3), RPDs stabilized in most conditions by the final measurement (i.e., after 12 minutes), suggesting this trial duration was likely adequate. The observed increases in perceived discomfort with higher duty cycles and payloads (Figure 4) are not surprising, given that both involved larger cumulative lumbosacral moments. Of note, final low-back RPDs increased linearly with payload in both duty cycle conditions (though at a higher rate in the 50 vs. 25% duty cycle). As such, responses to other payloads may be predictable with interpolation and perhaps to some extent by extrapolation. The rigid back vest appeared somewhat more effective, based on qualitative feedback, though low-back RPDs were somewhat higher (by a mean of 0.15, and not significantly) in this configuration.

As noted earlier, the primary goal of this study was to determine whether low-back loads would be tolerable when using the AD, and over what range. Based on perceived low-back discomfort (Figure 3), it appears the AD-induced moments are indeed tolerable over a wide range. Determining a specific tolerable range, though, requires some criteria, such as what level of discomfort is considered acceptable. If a “moderate” level is chosen (i.e., RPD = 3), then all combinations of duty cycles and payloads were acceptable. However, there are two cautions to consider with respect to this conclusion. First, trials were only conducted with six repeated cycles, for a total duration of 12 minutes. While RPD generally stabilized, as noted earlier, higher levels of discomfort may be involved with more prolonged use. Second, only mean responses are considered here. As such, roughly half of the participants reported higher values, and a more conservative approach may be warranted in future work (e.g., using 90th percentile values).

The second experiment supported the initial assumption regarding a tradeoff between shoulder and low back loads when using the AD for overhead work. Specifically, shoulder loads, as reflected in ratings of upper arm and shoulder perceived discomfort, were substantially reduced when using the ExoVest + Equipois arm. This benefit was particularly evident with heavier tools. However, and in contrast, low back loads increased as reflected again in ratings of perceived discomfort. Notably, though, the increases in low back loads with vest use were substantially smaller (and not statistically significant) than the decreases in shoulder loads. While the relative “costs” of shoulder vs. low back loads are difficult to assess, at a qualitative level the “total” costs may be reduced when using the vest.

As in the first study, joints load increased with increasing payload. Since low-back loads are induced by the Equipois arm as well as the payload, any reduction in arm weight would be beneficial. Also as in the first study, some cautions are warranted when making conclusions based on the study results. First, relatively brief periods of use were simulated. In contrast to the first study, perceived discomfort in the second study did not consistently reach plateau levels. Such levels did seem to be reached (or at least approached) for the upper extremity when using the vest (Figure 9). As such, conclusions about potential benefits for the upper extremity with vest use seem warranted. In contrast, perceived low-back discomfort appears to increase continuously over the trial, though the magnitudes of differences between vest conditions appeared to be relatively consistent over time. Second, moderate levels of perceived low-back discomfort were reported after only 10 minutes of use when using the larger tool masses. This, and the noted continued increases, suggests that more substantial levels of discomfort are likely with longer durations of use. As such, duration of use might need to be controlled when using the vest, and/or further studies conducted to assess long-term outcomes. Finally, while the ExoVest appeared to be effective overall, discomfort results and participant comments suggest that it may be best applied for situations involving heavier tools. In addition, participant responses indicated that some attention may be needed to the design specifically in cases involving arm raising activities (e.g., overhead work). Specifically, the shoulder strap became elevated when the arms were raised. To prevent or offset this, included thigh straps (as on a safety harness) may help keep the pelvis strap down. However, such a design change might also limit raising of the shoulder straps during arm elevation, and this may lead to additional shoulder discomfort and/or a decreased shoulder range of motion.

Key Points

- Low-back moments induced by the tested range of payloads, and when using the assistive device (vest), appeared to be at “tolerable” levels. However, this conclusion is based only on relatively short-term subjective responses, and relatively high levels of discomfort were reported by some participants especially in the more extreme conditions
- A back-mount vest design may be somewhat more effective than a front-mount design.
- When using the vest for overhead work, there is a tradeoff involved: shoulder loads decrease while low-back loads increase. However, the latter increase seemed to be smaller than the former increase.
- Acceptable levels of low back loads, when using the vest, may be exceeded with prolonged use.
- Use of the vest may provide the most benefit when using relatively heavy tools during overhead tasks.
- A redesign of the vest may help overcome some limitations related to movement of the vest relative to the torso.

5. References

Borg G. (1990). "Psychophysical scaling with applications in physical work and the perception of exertion." Scand J Work Environ Health 16(Suppl 1): 55-58.

Hermens H.J., B. Freriks, R. Merletti, D. Stegeman, J. Blok, G. Rau, C. Disselhorst-Klug and G. Hägg (1999). European recommendations for surface electromyography, Roessingh Research and Development The Netherlands.

Prieto T.E., J.B. Myklebust, R.G. Hoffmann, E.G. Lovett and B.M. Myklebust (1996). "Measures of postural steadiness: differences between healthy young and elder adults." IEEE Transactions on Biomedical Engineering 43(9): 956-966.

Veldpaus F. E., H. J. Woltring and L. J. M. G. Dortmans (1988). "A least-squares algorithm for the equiform transformation from spatial marker co-ordinates." Journal of Biomechanics 21(1): 45-54.

Wu G. and P.R. Cavanagh (1995). "ISB recommendations for standardization in the reporting of kinematic data." Journal of Biomechanics 28(10): 1257-1261.

Wu G., S. Siegler, P. Allard, C. Kirtley, A. Leardini, D. Rosenbaum, M. Whittle, D.D. D'Lima, L. Cristofolini, H. Witte, O. Schmid and I. Stokes (2002). "ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--part I: ankle, hip, and spine." Journal of Biomechanics 35(4): 543-548.