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Effect of an on-body ergonomic aid on oxygen consumption during a repetitive lifting task

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ABSTRACT

The purpose of this study was to determine if an on-body personal lift assistive device (PLAD)[1] affected oxygen consumption during a continuous lifting task and to investigate if any effect could be explained by differences in muscle activity or lifting technique. The PLAD, worn like a back-pack, contains a spring-cable mechanism that assists the back musculature during lifting, lowering, and forward bending tasks. Males ($n = 15$) lifted and lowered a box loaded to 10% of their maximum back strength at 6 times/minute for 15-minutes using a free-style technique under two conditions: wearing and not wearing the PLAD. Oxygen consumption was collected continuously for the first condition; then the participants rested until their heart rates returned to resting levels before repeating the protocol for the second condition. Knee flexion was monitored using Liberty sensors at the hip, knee, and ankle. EMG of the thoracic and lumbar erector spinae (TES, LES), biceps femoris, rectus femoris and gluteus maximus were gathered using a Bortec AMT-8 channel system. VO2 measures were averaged across the duration (15 min) for each condition. Results showed no differences between oxygen consumption during the PLAD and no PLAD conditions. When wearing the PLAD, the TES demonstrated an 8.4% EMG reduction when lowering the box while the biceps femoris showed a 14% reduction while lifting the box. Knee angles, used as a proxy for stoop or squat lifts, were highly variable for both conditions. In conclusion, the PLAD had no effect on oxygen consumption and, therefore, neither workers nor employers should increase the tasks demands when wearing this ergonomic aid.

Relevance to industry: While the PLAD reduced musculoskeletal effort required by back musculature, loads or rates of lifting should not be increased since there is no change in the overall physical demand of the task.

1. Introduction

Back pain is an industrial problem that affects 75–85% of workers at some point in their lifetime (Boos and Aebi, 2008). In 1999, the estimated prevalence of back pain in US industries was 17.6% (Guo et al., 1999) and, based on Freburger's et al. (2009) North Carolina study, the prevalence has continually increased from 1992 to 2006. Second only to headaches, back pain is the most commonly reported pain conditions of American workers and was shown to decrease productivity time by 3.2% during a two week period (Stewart et al., 2003). Despite our current understanding the incidence of back pain is increasing, in part, because many risk factors are unavoidable in industrial settings. Boos and Aebi (2008) cite some of the occupational risk factors for back pain including: heavy physical work, manual materials handling, repetitive motions, twisting and bending, frequent lifting, awkward postures and whole body vibration. In spite of ergonomic efforts to improve health and safety in the workplace, lowering the incidence of back pain is a major concern as it continues to affect many industrial workers across the industrialized countries.

Undoubtedly, the best approach to reduce risks of back injury is an ergonomic re-design of the jobs. However, not all jobs can be easily modified. For example, construction, forestry, masonry, and distribution may have difficulty modifying the workplace to improve the ergonomic design of the tasks. In some cases, off-body ergonomic solutions are used to reduce workers' risk of injury and, although off-body devices, such as carts and trolleys, are common for heavy awkward loads, they are often ineffective and time consuming when used to move lighter loads a short distance,

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[1] Commonly used Abbreviations are: Personal Lift Assistive Device (PLAD); Thoracic Erector Spinae (TES); Lumbar Erector Spinae (LES).

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especially when those loads are within our strength capability. The only previous on-body device commonly used in industry and touted to reduce injury were back belts. However, studies on the efficacy of back belts as an ergonomic aid to reduce or prevent workers' pain were inconclusive (McGill, 1993; Lavender et al., 2000) and the use of back belts was not supported by the US National Institute for Occupational Safety and Health (NIOSH, 1994).

Recently, a new on-body device called the Personal Lift Assistive Device (PLAD) has been developed and has undergone several laboratory and field tests. The PLAD was developed to reduce the physical demand of the back musculature by providing assistance for manual materials handling (MMH) tasks. The PLAD consists of elastic elements housed in a backpack-like device that lies almost parallel to the erector spinae (ES). An adjustable cable anchors one end of the elastic elements to the shoulders, while at the other end the cable runs through a pelvic spacer (to creates a better moment arm than the ES), down the back of the thighs, then into a shin pad before being anchored under the feet (Fig. 1a). When a worker bends forward the elastic elements are stretched thus acquiring elastic energy which offsets some of the upper body's weight. This stored elastic energy is released during the extension phase of the lift. A mathematical model proved the "off-loading" concept and this was supported by evidence collected during subject testing (Abdoli-Eramaki et al., 2007). The PLAD 'off-loading' reduced both compressive and shear forces at the L4/L5 lumbar discs and further research showed significantly reduced electromyographic (EMG) activity in both the thoracic and lumbar spinae between 14 and 27% in men and women across a variety of lifting techniques and loads (Abdoli-Eramak et al., 2006; Frost et al., 2009). Similar concurrent reductions in L4/L5 moments were also reported (Abdoli-E et al., 2006, 2008). When subjects wearing the PLAD were instructed to lift using a squat technique (a deep knee bend), there was a decrease in the erector spinae, latissimus dorsi, and biceps femoris EMG but an increase in rectus femoris and gluteus maximus EMG (Frost et al., 2009). These results indicated that the PLAD reduced the muscular demand in both back muscles and some leg muscles while other muscles increased their activity level. Other significant changes in muscular activation in the lower body were found but were varied and dependent on lifting technique (Frost et al., 2009).

The PLAD also reduced erector spinae fatigue in both men and women during a repetitive lifting task (Godwin et al., 2009; Lotz et al., 2009). When tested in an industrial setting, the PLAD reduced compression-normalized EMG of erector spinae activity without significantly increasing rectus abdominus activation or trunk flexion (Graham et al., 2009). In addition to reducing erector spinae activity, the PLAD also changed lifting kinematics such that users reduced lumbar and thoracic flexion and increased hip and ankle flexion (Sadler et al., 2011). Aside from lifting with a more upright trunk, other benefits that come with using the PLAD are improved dynamic stability of the back (Graham et al., 2011) and increased coordination during a continuous lifting task (Graham et al., 2012). All of these studies involved the assessment of risk factors for back pain, not the reduction of back pain itself.

While previous research has successfully investigated the PLAD's effect on muscular activation, there is no study investigating the PLAD's effect on oxygen demand. Several studies demonstrate an increase in oxygen demand of a squat lift over a stoop lift (Wang et al., 2012; Hagen et al., 1993; Welbergen et al., 1991). Differences in the oxygen demand are explained by the muscular activation required to move the body through a larger range of motion since squat lifts have more muscular activation compared to semi-squat or stoop lifts (Wang et al., 2012). However, squat lifts have no effect on the physical demand of erector spinae and gluteus maximus but do increase the demand on the quadriceps when compared to stoop lifts (Hagen et al., 1993). There is also increased activation of the quadriceps muscles during squat lifts compared to stoop lifts (Giat, Pyke, 1992). Evidently, lifting technique effects oxygen consumption and the muscle activation patterns of many large muscle groups.

The primary purpose of this study was to determine the PLAD's effect on oxygen demand during a highly repetitive lifting task using a relatively light load while a secondary purpose was to investigate if the differences in oxygen demand could be explained using electromyography of relevant muscles and knee bend as a proxy for changes in lifting technique. Despite the PLAD's ability to decrease the physical demand on the back musculature, it was hypothesized that there would be no difference in oxygen consumption as the PLAD requires other muscles to work harder. The rationale for this hypothesis stems from earlier work that showed: a) no heart rate changes were detected during a fatiguing task (Godwin et al., 2009; Lotz et al., 2009), b) some lower limb muscles increased their activity while other muscles decreased their activity (Frost et al., 2009), and c) lifters assumed a more-squat-like lifting pattern when wearing the PLAD (Sadler et al., 2011). As the PLAD reduces physical demands on the back, any workload increase by either the workers or the employer only serves to defeat the gains made in reducing back loading or muscular fatigue. Hence, an examination of the actual oxygen consumption demand is important.

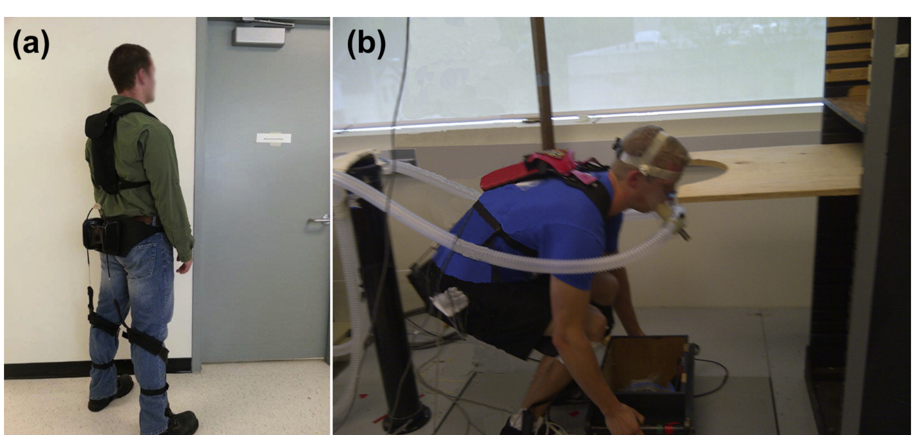

Fig. 1. (a) The Personal Lift Assistive Device contains springs in the backpack, a pelvic spacer to increase spring effectiveness and a cable that transfers forces to the shoulders and feet. (b) Oxygen consumption is measured during lifting and lowering task.

2. Materials and methods

A sample of convenience of fifteen male volunteers (22.1 ± 2.6 years, 1.81 ± 0.08 m and 81.6 ± 9.2 kg) were recruited from the local community. The exclusion criteria were no back pain or other musculoskeletal injuries in the last year and considering themselves to be fit enough to handle two 15 min bouts of the continuous lifting task. The duration of 15 min allowed participants sufficient time to reach steady state. The protocol was cleared by the University's Research Ethics Board prior to recruiting participants.

2.1. Instrumentation

The Moxus metabolic cart (AEI technologies, Bastrop, TX), an accurate and reliable measure of oxygen consumption (Medbø et al., 2012), was calibrated prior to subject arrival. A Bortex AMT-8 system with Multi Bio Sensors (Calgary Alberta) was used to collect electromyography (EMG). The Liberty system (Polhemus, Colchester, VT) was used to collect 3D position of the hip, knee and ankle. To determine back strength, an adapted ARCON Functional Capacity Evaluation System (Saline, MI) supported a load cell that was attached to a strap secured around the participant's chest. A custom Labview 8.6 (National Instruments Inc., Austin, TX) program collected the maximum voluntary effort during the back strength test, as well as EMG and positional data during testing. A switch on the bottom of the box identified lift-off and set-down of the box during lifting.

2.2. Preparation

Upon arrival, the protocol was described to the participant who signed a letter of informed consent. Then the participant completed the maximal isometric back strength test. From an erect standing position, with the pelvis resting against a support, the participant used their back to pull a harness attached to a uniaxial load cell. Ten percent of the maximal back strength was the load to be lifted during testing. The lifting table was adjusted to one-half of each participant's height. EMG electrodes were placed on the anterior superior iliac spine (ground), 2 cm to the right of the ninth thoracic vertebrae and third lumbar vertebrae, and at the midpoint of the gluteus maximus, biceps femoris, and rectus femoris as recommended by SENIAM (http://www.seniam.org/). Skin abrasion was performed and areas were cleaned with alcohol before applying the electrodes. To maintain signal amplitude throughout the test, Kryolan medical adhesive was put between EMG electrodes pairs before attaching them to the back (Abdoli et al., 2012). Foam spacers were taped around the electrodes to prevent contact with the PLAD. A heart monitor was placed around the chest. Before testing, the participant lay on their stomach for 6 min to determine resting heart rate which was based on the 10 s intervals averaged over the sixth minute. Next, the oxygen consumption mask was sized and fitted to the participant and Liberty markers were placed on the hip, lateral epicondyle and lateral malleolus and secured with tape or straps. The participant then completed some slow lifting maneuvers to ensure comfort and that there were no movement restrictions due to the instrumentation. Then, while standing at attention, a baseline trial was recorded and later used to ensure the consistent alignment of the Liberty sensors between conditions.

2.3. Testing

Participants completed 15 min of free-style lifting and lowering under both the control and PLAD conditions in randomized order (Fig. 1b). Participants lowered a box from a shelf to the floor and then lifted the box from the floor to the shelf at a rate of six lifts and lower per minute, paced by a metronome. Oxygen consumption and heart rate were collected for the entire 15 min. EMG and Liberty data were collected for 30 s intervals separated by 1 min with no collection. At the prescribed pace, each 30 s interval consisted of three lifts and three lowers. After completing the first 15 min condition the Liberty markers were removed and participants were instructed to lie carefully on their stomach and rest until their heart rates reached pre-test resting levels. Once their heart rate reached the targeted level, participants then rested for an additional 6 min. Similar to the first condition, heart rate was recollected over the sixth minute sampled on 10 s intervals, and then averaged to ensure its return to the initial resting heart rate. Liberty markers were reattached based on previously marked locations. The oxygen consumption mask was refitted prior to repeating the baseline standing posture and the 15 min test of the second condition.

Table 1
Summary of pretest subject information.

Variables	Mean	Standard deviation	Maximum value	Minimum value
Age (years)	22.1	2.6	28	19
Stature (cm)	181.3	8.0	197	166
Max back strength (kg)	89.4	15.8	109.9	57.9
Body mass (kg)	81.6	9.2	97.5	64
Box mass (kg)	8.9	1.6	11.0	5.8
Resting heart rate (beats/min)	62.9	9.8	78.1	44.5
Control heart rate (beats/min)	117. 7	17.0	146.8	90.5
PLAD heart rate (beats/min)	116.0	14.8	145.0	91.0
Control oxygen consumption (ml/kg/min)	17.9	2.4	12.7	19.1
PLAD oxygen consumption (ml/kg/min)	17.7	2.6	12.3	18.9

3. Analysis

All data collected from the study were imported and processed using MATLAB 7.12 (MathWorks, Natick, MA). Oxygen consumption was averaged across time producing a single average in oxygen consumption for each condition. Due to a technical error during testing, minute averages 6–10 of one subject were dropped from the analysis. SPSS Statistics Version 20 (Armonk, NYC) was used to compare the means of the two conditions using a paired *t*-test. Oxygen consumption was also averaged across each minute and these minute averages were then averaged again across all subjects. These group minute averages of oxygen consumption were plotted for both the PLAD (P) and the control (NP) using Microsoft Excel (2007, Redmond, WA). EMG data were de-trended to remove DC bias and then filtered using a 4th order Butterworth band pass filter between 20 and 450 Hz. Data were filtered again using a 4th order Butterworth notch filter between 59.5 and 60.5 Hz, and were then full wave rectified. Any spikes in the data that were greater than 6 standard deviations above the mean were replaced with the mean. Data were then re-filtered using a cut-off frequency of 3 Hz with a dual-pass 2nd order Butterworth filter. The processed signals were plotted over time and visually screened to drop obvious bad trials from the study. Processed EMG was separated into lifts and lowers based on the box switch data. Trials containing technical problems with the switch were manually digitized to locate the start and end of the trial. If this could not be done then the lift was dropped.

The mean curve of each muscle processed EMG was calculated within the lifting and lowering phases of each sampling period, and then a composite average across the full 15 min data collection was calculated for each muscle for each participant. This average was normalized to a percentage of the highest EMG activity ever experienced by that muscle during the entire 30 min of testing. SPSS was used to compare normalized means between conditions using a paired *t*-test ($p = 0.05$).

The baseline knee flexion angle was defined as the smallest angle found during a standing rest period and removed from the calculated maximum knee flexion angle experienced during each lift and lower. The maximum knee flexion angles were averaged across each condition for each subject. SPSS was used to compared maximum knee angle averages between conditions using a paired *t*-test ($p = 0.05$).

4. Results

A summary of the pretesting subject information is shown in Table 1. These data show that participants were fairly homogenous and typical of young males. Fig. 2 displays the minute average relative oxygen consumption (ml/kg/min) of all 15 subjects for the duration of testing for both conditions. Overall there were no significant differences ($p = 0.49$) in the relative oxygen consumption between the control and PLAD conditions. Across all subjects the average (standard deviation) value for the 15 min task at 6 lifts/lowers per minute was 17.7 ml/kg/min (±2.6 ml/kg/min) for the PLAD condition and 17.9 ml/kg/min (±2.4 ml/kg/min) for the control condition. The standard deviations shown in Fig. 2 are more reflective of the energy demand between subjects than within subjects. Across both conditions, using 10% of maximal back static strength, the average box weight was 8.9 ± 1.6 kg.

The mean normalized EMG activity of all muscles is displayed in Table 2 along with the significance values. For lifts, EMG activity of the hamstring's biceps femoris was found to be lower ($p = 0.014$) for the PLAD condition (70.4%) than the control condition (78.8%). There were no differences between conditions for the mean normalized EMG activity of the rectus femoris, thoracic erector spinae, lumbar erector spinae, and gluteus maximus. For lowers, the mean normalized EMG activity of the thoracic erector spinae was lower ($p = 0.032$) for the PLAD condition (43.5%) when compared to the control condition (57.5%). There were no differences between conditions for the mean normalized EMG for the remaining muscles.

The maximum knee angle was used as a proxy for a change in technique during lifts and lowers when wearing the PLAD. No differences were found in maximal knee bend for either lifts (PLAD = 71.8°±°19.0°; Control = 72.8°±°18.3°) or lowers (PLAD = 67.0°±°20.7°; Control = 68.4°±°19.6°). The maximal knee bend was highly variable as shown by the standard deviations within subjects and across conditions.

Table 2
Summary of means and standard deviations of EMG activity levels for all muscles and conditions.

Muscle	Condition	Lift/lower	Normalized mean EMG (%)	Standard deviation	*P* value
TES	NP	Lift	75.2	10.7	0.158
TES	P	Lift	64.7	20.1	
TES	NP	Lower	57.5	13.0	**0.032***
TES	P	Lower	43.5	16.8	
LES	NP	Lift	75.6	9.5	0.765
LES	P	Lift	78.0	6.6	
LES	NP	Lower	43.0	10.5	0.120
LES	P	Lower	43.1	10.5	
Rectus Femoris	NP	Lift	62.4	11.0	0.301
Rectus Femoris	P	Lift	57.2	13.3	
Rectus Femoris	NP	Lower	56.7	11.6	0.644
Rectus Femoris	P	Lower	58.7	12.2	
Gluteus Maximus	NP	Lift	70.1	18.3	0.241
Gluteus Maximus	P	Lift	75.4	9.3	
Gluteus Maximus	NP	Lower	26.5	8.0	0.416
Gluteus Maximus	P	Lower	28.5	6.7	
Bicep Femoris	NP	Lift	78.8	6.3	**0.014***
Bicep Femoris	P	Lift	70.4	7.7	
Bicep Femoris	NP	Lower	38.1	10.6	0.085
Bicep Femoris	P	Lower	32.2	7.1	

*indicates accepted significance level of $p \leq 0.05$. *indicates significance.

5. Discussion

The findings reveal that the PLAD had no effect on oxygen consumption and confirm our hypothesis, and previous results, that showed no change in heart rate as a result of wearing the PLAD (Lotz et al., 2009; Godwin et al., 2009). Our data also confirm that workers experienced the same energy demand during a continuous lifting task regardless of whether the PLAD was worn or not. Although these results cannot be generalized to other lifting rates and loads lifted/lowered, they provide convincing evidence that workloads should not be increased for high lifting rates of relatively light loads because of wearing this assistive device.

Our average oxygen consumption of 17. 8 ml/kg/min (1456.8 mL/min) were higher than those of Marley and Duggasani (1996) who reported values of 936.3 mL/min when lifting a 7 kg box at 6 lifts per minute for 15 min using a freestyle lifting technique. This seems reasonable since the average weight lifted in our study was 8.9 kg versus 7 kg for Marley and Duggasani (1996). Additional differences in oxygen consumption for the current study were probably due to

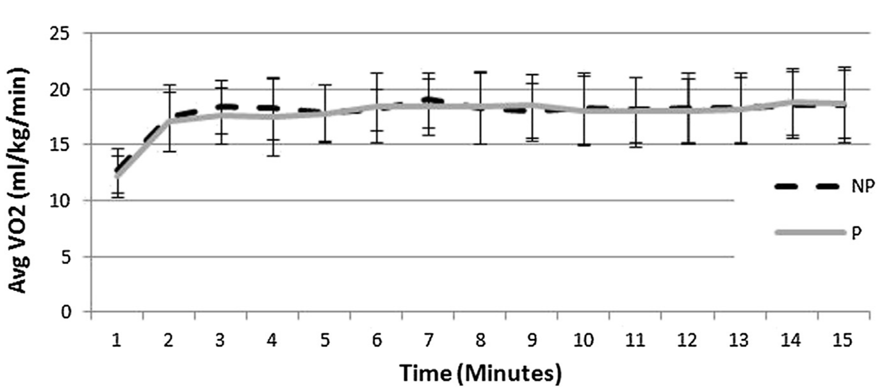

Fig. 2. Average Relative Oxygen Consumption (in ml/kg/min) of all 15 Subjects over time for the PLAD (P) and No-PLAD (NP) conditions.

differences in subject aerobic capacity, self-selected lifting technique, differences in lifting experience and masses lifted.

The rationale for collecting EMG and knee position data was to explain the oxygen consumption results. In terms of EMG, it was expected that the PLAD would decrease activity in TES and LES, regardless of lifting technique (Abdoli et al., 2006, 2008). The expected decreases in TES and LES activity occurred in some participants but not all. While TES and LES activity were not different between conditions during lifting, the TES activity was reduced by 8.4% during lowering. One possible explanation for less consistency in the reduction of erector spinae amplitude with PLAD was the normalization strategy; EMG was normalized to the maximum activity ever experienced in that muscle for the duration of testing. Previous researchers had used percentage of maximal effort (Abdoli et al., 2006, 2008). In addition, the PLAD may have interfered with the LES and TES electrodes since their placement was directly under the PLAD. As well, the decision to allow a freestyle lifting technique may have resulted in greater variability across participants in terms of using the squat semi-squat or stoop lift styles (Wang et al., 2012). Another concern was the broad distribution of oxygen consumption measures which ranged from 19.3 to 32.5 ml/kg/min, an indication that some participants had lower fitness levels or aerobic capacity which might have led to fatigue in specific muscles which affected their lifting techniques (Trafimow et al., 1993; Cheng, 2000).

In terms of lower limb muscle activity, the PLAD reduced biceps femoris activity by 14.0% ($p = 0.014$) during lifting but not during lowering ($p = 0.085$). Frost et al. (2009) found this result as well but also found that the gluteus maximus was significantly lower during stoop lifts; however, not during squat lifts. The differences may be due to the version of the PLAD being tested. The PLAD has a pelvic spacer to position the spring force across the pelvis with the upper edge at the L5/S1 joint and lower edge at the hip joint. In the Frost et al. (2009) study this pelvic spacer was 150 mm whereas in this study it was 100 mm. Frost et al. (2009) also found that the quadriceps activity (vastis lateralis, vastus medialis and rectus femoris) increased during squat lifts but not stoop lifts. The rectus femoris in this study did not show these same increases, perhaps due to the freestyle lifting technique. In addition, Sadler et al. (2011) found that the PLAD promoted a change to a more squat-style technique. However, in the current study the knee angle, which was used as a proxy for stoop or squat lifting techniques, did not indicate any systematic change toward a squat lifting technique. Therefore, it is not possible to see systematic changes in muscular activity in the lower limb or lifting technique as a result of wearing the PLAD.

The results of this study were obtained from young males; however, when taking into consideration previous studies, it is expected that these results can also be applied to other populations. Godwin et al. (2009) studied 12 females and found the PLAD to decrease fatigue variables in both the thoracic and lumbar erector spinae with no change in heart rate responses across conditions. With this decreased activation of the erector spinae, other muscles would be expected to compensate during loading of the PLAD's spring component. Changes in EMG and moments were also similar for men and women (Abdoli-E et al., 2006, 2008). Similarly, it can also be expected that the PLAD would have the same effect on older populations. Based on currently available knowledge of the PLAD, it is expected to alter the muscular activation pattern of the user's lift, and thus cause no change to physiological demand regardless of age or sex.

In summary, we have shown that oxygen consumption, and thus energy demand, is not altered when wearing the PLAD. A passive system like the PLAD can only use the spring's energy when they are stretched during lifting, lowering and forward bending. When stretched the PLAD's springs apply a reaction force against the shoulders, pelvis and feet to create supportive tension. Hence, energy is internal to the person-PLAD system and so it is reasonable that the total energy demand for a task is also unchanged. However, it is also reasonable that, if the extensor muscles of the body are assisted by the PLAD, other muscles must work somewhat harder. This energy demand finding when wearing the PLAD are critical to future use of this ergonomic aid in industry. Neither workers nor management should increase the load lifted, task frequency or task duration when wearing the PLAD as this will result in an increased metabolic workload for relatively light loads at high lifting/lowering rates.

As mentioned earlier, the best method to reduce injury among manual materials handlers is through improved ergonomic job design by eliminating the back pain risk factors. When this is not possible, either "off-body" or "on-body" ergonomic aids may be considered as they would reduce some of the back pain risk factors. However, such assistive devices must be subjected to rigorous scrutiny before introducing them into the workplace since their true impact cannot be evaluated until there are a sufficient number of users. For example, the PLAD has undergone many studies to assess its effectiveness, safety and user acceptability. Yet despite all of these studies, only its impact on risk factors for back pain is known, but not whether it reduces back pain itself. What is the impact of long term PLAD use? What lifting and forward bending tasks are best suited to PLAD use? These questions can only be answered when MMH companies have adopted the device in larger numbers for an extended period of time. Unlike the lifting belts that were introduced into the workplace without adequate scientific scrutiny, the PLAD has a better chance to help workers based on its ability to impact a number of back pain risk factors, including its impact on the energy demands of lifting and lowering tasks.

6. Conclusion

In summary, wearing the PLAD does not alter the oxygen consumption during a free-style lifting and lowering task. Since the task demand is the same, and the oxygen consumption is the same in both the PLAD and No-PLAD conditions, some muscles will be assisted as a result of the spring tension while others must work harder. This study provides partial evidence for this effect for a highly repetitive lifting and lowering task. Based on the PLAD's design, the extensor muscles of the back and lower limb are assisted during lifting, lowering and forward flexed postures.

This study has broad implications for use in industry. Although this ergonomic aid has consistently demonstrated reduced back muscle activity, moments of force and muscular fatigue, findings supported by workers' opinions, it will not reduce the total energy demands of the job. Therefore, workers and management should not expect to complete more work just because they are wearing the PLAD. This device has consistently shown it will reduce back muscular demand but, based on this study, not metabolic demands.

Acknowledgments

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