Physical Ergonomics and Human Factors, Vol. 103, 2023, 135–143
https://doi.org/10.54941/ahfe1003044

Exploration of Back Exoskeleton's Effectiveness on Transportation Maintenance Workers During Lifting Activities

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ABSTRACT

Safety statistics from Indiana Department of Labour showed that the transportation and warehousing industry has the second highest number of reported occupational fatalities (26) in 2020. One major cause of occupational fatalities is ergonomic issues including excessive force, repetitive motion, and awkward posture. These ergonomic issues have already been extensively studied and corresponding solutions were developed for the building construction activities. However, transportation activities are different from building construction activities in duration, intensity, and frequency. In addition, there lacks studies exploring whether the proposed solutions to ergonomic issues of building construction could also solve the ergonomic issues of transportation activities. To this end, field experiments were conducted with 29 transportation maintenance workers between August 9th 2023 and September 23rd 2023 at a transportation maintenance unit of Indiana Department of Transportation (INDOT). Lifting bags of dry concrete mix was identified as the activity of top concern, according to (1) the perception of which activity most likely to cause an injury to back or shoulder, (2) the frequency of performing the activity, and (3) the number of historical sprain injuries caused by the activity. Therefore, the participants were asked to lift 12 bags of three different weight of dry concrete mix with and without a back exoskeleton. Specifically, three different weights of bags include: 80-pound bags (weight of bags that INDOT maintenance workers mostly use), 50-pound bags (weight of bags that INDOT maintenance workers sometimes use and which is recommended by Recommended Weight Limit equation under the ideal condition), and 31.5-pound bags (recommended weight of bags based on applying values from real lifting practice of INDOT maintenance workers into the Recommended Weight Limit equation). The participants need to lift bags from a pallet to a truck with liftgate, have a five-minute short break, offload those bags from the truck with liftgate to the ground, and then have a 20-minute break. Skin conductance and heart rate, as the key indicators of physical fatigue, were measured during the lifting activity. In addition, perceived level of muscle exertion was also collected by using a Borg 6–20 scale during two experiment breaks of each trial for indicating level of fatigue risk level from low to very high. After performing a paired t-test of collected data, it shows that the back exoskeleton does not significantly help workers reduce physical fatigue risks while transportation maintenance workers lift 31.5-pound bags. However, the back exoskeleton can significantly lower the physical fatigue risks when transportation maintenance workers lift 50-pound bags and 80-pound bags. This study not only fills the gap of exploring the effectiveness of back exoskeleton implementation in transportation maintenance activities, but also provides evidence and practical recommendations for transportation workers, managers, and organizations that a back exoskeleton could reduce the level of fatigue risk when lifting materials with weight of 50 pounds and above.

Keywords: Transportation maintenance, Ergonomics, Exoskeletons, Lifting activities

INTRODUCTION

According to the United States Bureau of Labor Statistics, around 93% of construction laborers were required to lift or carry medium or heavy levels of weight in 2020 (Petosa and Helmick). Such an overexertion in lifting or other physically demanding activities is one major ergonomic reason for the occupational fatalities and injuries. In 2020, construction laborers experienced the highest number of fatal injuries and the highest rate of nonfatal incidence due to overexertion (Petosa and Helmick), and the construction industry and the transportation industry had the highest number of occupational fatalities (Indiana Department of Labor, 2021). Therefore, it is important to measure the extent of physical fatigue of construction laborers and determine effective solutions to reduce the risk of overexertion.

The extent of physical fatigue varies due to types of construction activities, types of projects, physiological characteristics (i.e., age, gender, weight, height, health conditions) of laborers. Construction laborers are involved in diverse types of construction activities, such as carrying materials, lifting materials, and plastering (Zhu et al. 2021). Compared to laborers operating equipment, those who actually perform manual work such as lifting were prone to higher level of physical fatigue (Abdelhamid and Everett 1999). Previous studies also found that older workers are likely to get tired because of worse muscle strength and work capacity compared to younger workers (Faulkner et al. 2007, Kenny et al. 2008). However, limited studies on physical fatigue have differentiated building construction activities from transportation maintenance activities, which differ in duration, intensity, and frequency.

Exoskeletons are regarded as one effective way for construction industry to decrease fatigue and prevent occupational injuries or fatalities. Different types of exoskeletons can be used to assist back, shoulder, arm, and leg (Howard et al. 2020). Exoskeletons can help laborers perform different kinds of construction activities, such as lifting or carrying heavier loads (Anderton, Sarcos 2018) and semi-squat lifting movement (Wei et al. 2020). Nevertheless, there is a lack of studies on the effectiveness of back exoskeleton on transportation maintenance workers for lifting activities.

This study aims to explore the impact of back exoskeleton on the physical fatigue of transportation maintenance workers during different levels of lifting activities. Results of this study can help transportation workers, managers, and organizations realize the effectiveness of back exoskeletons during lifting activities.

LITERATURE REVIEW

Physiological characteristics of construction workers can be measured by diverse physiological metrics, such as heart rate, skin temperature, heart-rate variability, electromyography, oxygen consumption, skin conductance, and muscle engagement (Abdelhamid and Everett 1999, Abdelhamid and Everett 2002, Ahn et al. 2019, Anwer et al. 2021, Hallowell 2010, Umer et al. 2017). Among these metrics, cardiac activity and skin response, which can be measured by heart rate and skin conductance respectively, are used to evaluate the physical workload and physical fatigue (Ahn et al. 2019).

The change in heart rate is highly related to multiple indicators, such as workload (Jankovský et al. 2018), frequency (Alferdaws and Ramadan 2020, Ghaleb et al. 2019), rest time (Kazar and Comu 2022), and the height for lifting activities (Li et al. 2009). Most research applied the fatigue levels classified by heart rate by Astrand and Rodahl (1986), which defines light work with a mean heart rate up to 90 beats/minute, moderate work with a mean heart rate of 90~110 beats/minute, and heavy work with a mean heart rate of 110~130 beats/minute, etc. Most studies recognized that an increase in heart rate implied the presence of fatigue or higher level of fatigue during different construction activities (Abdelhamid and Everett 1999, Chan et al. 2012, Das 2014, Roja et al. 2006, Yin et al. 2019).

Skin conductance, also known as electrodermal activity, is another metric for the extent of physical fatigue. It can be calculated by a current flow between two points of skin contact (Braithwaite et al. 2013). The increase in skin conductance can be caused by the production of sweat which promotes the flow of electric current (Mohanavelu et al. 2017). Higher skin conductance responses were associated with more post-task physical fatigue of participants with chronic fatigue syndrome compared to healthy participants (Rimes et al. 2016). However, there is a lack of studies on measuring skin conductance among transportation maintenance activities.

In addition, the perceived muscle exertion is viewed as an indicator of physical strain, which varies from different types of activities (Borg, 1982). Most studies using the perceived exertion in construction industry followed the rules of Borg rating of perceived exertion (RPE) scale (Aryal et al. 2017, Gram et al. 2012, Umer et al. 2020). Nevertheless, limited studies have focused on testing the perceived exertion of transportation maintenance workers during lifting.

To address the above research gaps, this study evaluated the extent of physical fatigue based on heart rate, skin conductance, and perceived muscle exertion. Following sections explain the detail of field experiments, demographic information, and the influence of back exoskeletons on three physiological metrics.

METHOD

Lifting bags of dry concrete mix was identified as the activity of top concern, according to (1) the perception of which activity most likely to cause an injury to back or shoulder, (2) the frequency of performing the activity, and (3) the number of historical sprain injuries caused by the activity. Therefore, field experiments were conducted with 29 transportation maintenance workers of Indiana Department of Transportation (INDOT) by requesting them to lift bags of dry concrete mix. Data was collected between August 9th 2023 and September 23rd 2023 at a transportation maintenance unit. Specifically, a demographic survey was first finished with each participant to gather information of their gender, age, height, etc. Then, the researcher assisted each participant with wearing a heart rate and skin conductance sensor (E4 wristband from Empatica) on the participant's wrist. After that, the participant was asked to lift 12 bags of three different weights of dry concrete mix with and without a back exoskeleton. The first tested weight is 80-pound bags (INDOT maintenance workers mostly use). The second tested weight is 50-pound bags (INDOT maintenance workers sometimes use and recommended by Recommended Weight Limit equation under the ideal condition). The third tested weight is 31.5-pound bags (recommended weight of bags based on applying values from real lifting practice of INDOT maintenance workers into the Recommended Weight Limit equation). Since there are two parameters in the experiment: back exoskeleton (with/without) and weights (80 pounds (lbs.), 50 lbs., and 31.5 lbs.), each participant needed to complete six trials. The trail sequence was generated by a Balanced Latin Square to remove the order effect and carry over effect. In each trial, the participant needed to lift bags from a pallet to a truck with liftgate, have a five-minute short break, offload those bags from the truck with liftgate to the ground, and then have a 20-minute break. Skin conductance and heart rate, as the key indicators of physical fatigue, were measured during the lifting activity. In addition, perceived level of muscle exertion was also collected by using a Borg 6–20 scale during two experiment breaks of each trial for indicating level of fatigue risk level from low to very high on shoulder, arm, back, upper leg, and lower leg muscles. Paired t test was then performed for data analysis.

RESULTS AND DISCUSSION

Demographics of Participants

The majority of participants are male (27; 93.10%). Most participants are level-three highway technicians (14; 48.28%), followed by level-one highway technicians (6; 20.69%), supervisors (5; 17.24%), level-two highway technicians (2; 6.90%), and safety specialists (2; 6.90%). As shown in Table 1, the demographic information of participants was summarized, consisting of age, body size, body mass index (BMI), and body fat percentage, etc. The mean age of participants was 37.45±9.81 years. The mean BIM was 30.58±5.96, indicating that participants were likely to be overweight and have obesity according to the standard weight status categories (Centers for Disease Control and Prevention, 2022). The mean value of body fat percentage (28.21±9.97) also showed the possible overweight of participants.

Table 1. Demographics of participants.

Demographics	Mean	Standard deviation
Age (year)	37.45	9.81
Height (inch)	70.79	3.31
Arm (inch)	27.72	2.12
Shoulder height (inch)	61.14	2.43
Waist height (inch)	37.86	2.94
Knee height (inch)	22.50	3.40
Waist size (inch)	39.21	6.47
Weight (lb)	218.54	49.79
Body mass index	30.58	5.96
Body fat percentage (%)	28.21	9.97
Fat free body weight (lb)	151.76	20.81
Subcutaneous fat (%)	24.02	8.96
Visceral fat	13.16	6.00
Body water percentage (%)	51.74	7.41
Skeletal muscle (%)	47.34	7.87
Muscle mass (lb)	144.09	19.95
Bone mass (lb)	7.69	0.89
Protein (%)	16.39	2.55
Basal metabolic rate (kcal)	1856.72	203.65
Metabolic age (year)	38.44	10.23
Tenure (year)	3.96	3.88

Impact of Back Exoskeleton on Heart Rate and Skin Conductance

As seen in Table 2, for each level of weight, the heart rate of participants was compared between wearing and not wearing back exoskeletons. According to the fatigue levels by Astrand and Rodahl (1986), lifting bags of 31.5 lbs. and 50 lbs. belongs to light work with the heart rate less than 90 beats/min, while lifting bags of 80 lbs. is a moderate work with the heart rate between 90 and 110 beats/min for these maintenance workers. Regardless of different weights, wearing back exoskeletons resulted in a lower heart rate than not wearing them, indicating back exoskeleton can lead to less physical fatigue for maintenance workers during lifting activity. In addition, a significant difference exists in lifting bags of 50lbs. and 80lbs., implying that back exoskeletons particularly help workers lifting 50-pound and 80-pound bags. Table 3 compared the heart rate among different weights under wearing and not wearing exoskeletons. The significant difference exists in each pair of t tests, meaning that lifting heavier loads led to higher heart rate and higher risk of physical fatigue.

As seen in Table 4, the skin conductance was compared between trials with and without back exoskeletons under three weights. Regardless of the level of weights, wearing a back exoskeleton always led to a decrease in skin conductance. This also proved the effectiveness of back exoskeletons on these workers during the lifting task. However, the significance test showed that a back exoskeleton was the most useful for lifting bags of 50 lbs. Table 5 presented the comparison of skin conductance among different weights under

Table 2. Heart rate comparison between wearing back exoskeleton and not wearing exoskeleton under three different weights (beats/minute).

31.5 lbs.		50 lbs.			80 lbs.		
With	**Without**	**With**	**Without**		**With**	**Without**	
75.88	76.78	86.78	90.77	*	92.42	100.71	*

* Significant

Table 3. Heart rate comparison among different weights under wearing and not wearing exoskeleton (beats/minute).

With						Without					
31.5 lbs.	**50 lbs.**		**50 lbs.**	**80 lbs.**		**31.5 lbs.**	**50 lbs.**		**50 lbs.**	**80 lbs.**	
75.88	86.78	*	86.78	92.42	*	76.78	90.77	*	90.77	100.71	*

* Significant

Table 4. Skin conductance comparison between wearing back exoskeleton and not wearing exoskeleton under three different weights (microSiemens).

31.5 lbs.		50 lbs.			80 lbs.	
With	**Without**	**With**	**Without**		**With**	**Without**
4.47	5.99	11.05	14.89	*	25.84	26.34

* Significant

Table 5. Skin conductance comparison among different weights under wearing and not wearing exoskeleton (microSiemens).

With						Without					
31.5 lbs.	**50 lbs.**		**50 lbs.**	**80 lbs.**		**31.5 lbs.**	**50 lbs.**		**50 lbs.**	**80 lbs.**	
4.47	11.05	*	11.05	25.84	*	5.99	14.89	*	14.89	26.34	*

* Significant

wearing and not wearing exoskeletons. The significant differences in each paired t tests indicated that an increase in weight could bring more risk of physical fatigue to transportation maintenance workers when performing lifting tasks.

Impact of Back Exoskeleton on Level of Muscle Exertion

As shown in Table 6, the perceived muscle exertion of different body parts was compared between trials with and without back exoskeletons under three weights. According to the Borg RPE scale, transportation maintenance workers experienced low and moderate fatigue level during lifting bags of 31.5 lbs. and 80 lbs., respectively. When lifting bags of 50 lbs., only in trials without back exoskeletons did the workers perceive moderate fatigue in theirs backs (RPE: 11.96) and upper legs (RPE: 11.48). Besides, significant differences of the perceived exertion exist in five situations as shown in Table 6,

Table 6. Level of muscle exertion comparison.

Muscles	31.5 lbs.		50 lbs.			80 lbs.		
	With	Without	With	Without		With	Without	
Shoulder	8.71	8.73	10.34	10.44		12.61	13.34	*
Arm	8.93	8.98	10.93	10.94		13.07	13.41	*
Back	9.23	9.29	10.71	11.96	*	12.64	13.24	*
Upper leg	8.89	8.95	10.38	11.48	*	12.10	11.63	
Lower leg	8.53	8.58	9.95	9.97		11.34	10.92	

* Significant

indicating the effectiveness of back exoskeletons on (1) back and upper leg during lifting 50 lbs., (2) and shoulder, arm, and back during lifting 80 lbs.

CONCLUSION

This study conducted field experiments to explore the effectiveness of back exoskeletons on transportation maintenance workers during lifting three weights. Research findings show that workers experienced low and moderate fatigue when lifting no more than 80 lbs., and back exoskeletons can significantly reduce physical fatigue when lifting 50 lbs. and 80 lbs. However, further standard fatigue levels based on each physiological metric are needed to be specifically determined for different types of industry and construction activities.

ACKNOWLEDGMENT

This work was supported in part by the Joint Transportation Research Program administered by the Indiana Department of Transportation and Purdue University. The authors would also like to thank Barry Partridge and Michael Lane for their help. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the sponsoring organizations. These contents do not constitute a standard, specification, or regulation.

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