The Assist Performance Test of Industrial Passive Waist-assistant Exoskeleton on Fatigue during a Repetitive Lifting Task

Dezheng Zeng¹, Shengguan Qu ¹,b, Tao Ma², Peng Yin¹,a, Hongyun Gao³, Ning Zhao², Yumeng Xia³

¹ School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, Guangdong, China

² State Key Laboratory of Smart Manufacturing for Special Vehicles and Transmission System, Inner Mongolia First Machinery Group Co., Ltd., Baotou, Inner Mongolia, China

³ China North Ordnance New Technology Generalization Institute, Beijing, China

a e-mail: 201821002525@mail.scut.edu.cn

b e-mail: qusg@scut.edu.cn

Abstract: Low back pain is a serious industrial problem and a common chronic disabling disease that affects the health of many workers, with a steadily rising rate of incapacity due to low back pain and a burden on individuals, families, businesses and society. Therefore, a new type of wearable lifting assist device, called the Industrial Passive Waist-assistant Exoskeleton (IPWE), was developed for workers' working conditions to reduce the risk of lower back muscle damage during manual handling. The purpose of this study was to evaluate the impact of this IPWE on the muscle activity and oxygen consumption of the lower back in simulated lifting tasks. Meanwhile, local perceived stress, subjective perceived fatigue and system availability of the exoskeleton system were evaluated. The results showed that the IPWE significantly reduced the muscle activity of the thoracic erector spinae and lumbar erector spinae. During the 15-minute repetitive lifting task, the electromyographic amplitudes of the thoracic erector spinae TES1, TES2 and the lumbar erector spinae LES1, LES2 decreased by 19.14%, 14.63%, 28.03% and 25.05%, respectively. In addition, the exoskeleton did not cause significant differences in oxygen consumption and subjectively perceived fatigue. But it caused increased local pressure on the thighs and shoulders. Among them, IPWE was considered to have acceptable availability by half of the subjects. However, the obvious contact pressure on certain body parts were the cause of discomfort caused by IPWE.

1. Introduction

Low back pain is a serious industrial problem and a common chronic disabling disease, which would cause burden to individuals, families, businesses and society [1]. It is especially common in jobs that require manual handling such as construction, agriculture, mining, and storage. The proportion of work ability loss caused by low back pain has been steadily increasing. It affects the health of many workers, has a negative impact on the quality of life of workers, and significantly increases the...
compensation costs of enterprises. Studies have shown that as many as 80% of adults will be affected by it at some time in their lives, and 4-5% of the population suffers from acute low back pain every year [2]. In the entire industrialized world, low back pain is the main cause of restricted activity, absenteeism, and reduced productivity. It threatens workers’ motor functions, mental health and quality of life [3]. It makes individuals, companies, or society suffer a huge direct and indirect cost in health, society and economy [4].

Although automation technology is now widely used in the industry, in fact many tasks still need to be performed manually by workers. Because in these tasks, workers are required to observe and make decisions, or these tasks depend on human accuracy, skills and free movement ability [5]. Therefore, in order to reduce the incidence of pain and injury in these manual handling occupations without affecting productivity, mechanical isolated handling aids (such as cranes or trolleys) are usually used to assist in handling loads that exceed human capacity. In addition, people are paying more and more attention to and researching wearable robotics (including exoskeleton) to help workers perform manual handling tasks without risk [6]. The power-assisting devices currently used on the human body are usually carrying straps, but these belts have not undergone any research to evaluate their ability to reduce low back pain, and there is no conclusive evidence that these straps have effective safety protection function for workers while performing manual handling tasks [7].

As a result, we further study the free individual waist protection device for the working conditions of the workers to prevent the injuries caused by the workers in the manual tasks and reduce the prevalence of the manual tasks. At present, our laboratory and enterprises have jointly developed a new type of wearable lifting assist device, which called Industrial Passive Waist-assistant Exoskeleton (IPWE), which is used to reduce the risk of waist and back muscles injury of workers during manual handling work. Although the subjects felt a subjective difference when lifting heavy objects while wearing IPWE, the objective effectiveness of this exoskeleton in alleviating fatigue is still unclear. Therefore, the purpose of this research is to evaluate the influence of this IPWE on the muscle activity and oxygen consumption of the lower back during the simulated lifting task by testing subjects performing simulated lifting tasks, and the local perceived pressure of the exoskeleton system, subjective perceived fatigue and system availability are evaluated.

2. Method

2.1. Participants

In this study, there are 8 healthy subjects, with an average age of 26 (SD 7), an average weight of 73.2 (SD 9.4) kg, and an average height of 177 (SD 6.5) cm, which volunteered to participate in the study. None of the participants have reported a history of muscle strain and low back pain in the past three months. Subjects signed an informed consent form after being notified of the experimental procedures. A 5-minute warm-up was performed before the experimental test.

2.2. Industrial passive waist-assistant exoskeleton

In this study, IPWE is a passive wearable exoskeleton, including chest support, waist elastic units, leg supports and several webbing components (Figure 1). IPWE can assist workers to complete their promotion tasks through a non-mobile mechanism. This external "on-body" IPWE is the concept of simulating human muscles by using elastic elements that can be considered as external muscle power generators. These elastic elements are almost aligned parallel to the erector spinaes and leg muscles. IPWE uses the elastic elements on both sides of the chest support unit and hip joint to provide assistance for the bending and transportation process; the straps connecting the shoulders and the leg binding units to reduce the fatigue of the waist through mechanics pass during the transportation process. IPWE is worn by the subject like a backpack. After putting it on, the straps on the back, waist, and thighs need to be fixed and adjusted or aligned. The first time it is worn, a researcher is required to assist. The whole wearing process takes about 1 minute. Before the formal test, the subjects need to walk and carry normally until the straps and elastic elements are adjusted to the appropriate range.
2.3. Instrumentation

A four-channel portable Flexvolt Bluetooth EMG Sensor (sampling rate: 2048 Hz) was used to collect the surface EMG data of the thoracic erector spinae (TES) and lumbar erector spinae (LES) muscles on the left and right sides. A pair of Ag/AgCl electrodes oriented parallel to the muscle fibers was placed on each muscle abdomen with a distance of 20 mm between the electrodes. The reference electrode is placed in a neutral position on the side perpendicular to the orientation of the muscle fiber. Before fixing the Ag-AgCl electrode with tape, scrub the skin surface. The oxygen consumption measurement is carried out using the VO2 Master Health Sensor equipment, and each subject needs to wear it for information entry and calibration before the formal measurement. Each subject performed Maximum Voluntary Contraction (MVC) once before the start of all tests. The weight used in the experimental lifting task was 20% of the subject’s MVC.

![Figure 1](image1.png)

(a) (b)

Figure 1. The structure diagram of IPWE used in the tests consisting of a shoulder straps, chest support, waist straps, waist elastic units and leg supports, showed in two views: (a) front view; (b) rearview.

![Figure 2](image2.png)

Figure 2. The electrodes placed on the back. The EMG of thoracic erector spinae (TES) and lumbar erector spinae (LES) are collected by Ag/AgCl electrodes.

2.4. Testing procedures

2.4.1. Preparation

The experiment environment is kept at a constant temperature of 22°C, and electronic devices such as mobile phones are turned off before the experiment to reduce signal interference. After the subjects enter the laboratory, the laboratory staff will demonstrate the rules of wearing and using the test related equipment, and introduce the test process in detail until the subjects are proficient and can complete the lifting task at a constant speed according to the metronome. After the training is completed, the subjects will carry out 2 groups of 15-min handling experiments (with/without exoskeleton) in a random order, with an interval of more than 24 hours between each experiment. Before all experiments, it is necessary to confirm that the subjects have no muscle discomfort.
2.4.2, Lifting tasks
The lifting task starts when the subject remains relaxed and upright. The subject lifts the heavy object on the ground directly in front with a free posture at the designated position, and puts the heavy object on the table at the same height as the waist after returning to the upright position. And then put the heavy object back on the ground and restore it upright (Figure 3). The whole process was controlled by a metronome to maintain a constant speed. Each subject completed 75 groups within 15 minutes, and collected the subjects’ oxygen consumption information and electromyographic signals during this period.

Figure 3. A subject was performing the whole lifting process with the exoskeleton. The toolbox was set at 20% MVE of the subject and the table had been adjusted to the waist height.

2.4.3, Subjective responses
Local Perceived Pressure (LPP) score is performed after a single lifting task [8]. The LPP rating from 0 (no pressure at all) to 10 (extremely strong pressure) is used to assess the musculoskeletal pressure felt in areas in close contact with IPWE, including the shoulders, waist and thighs. During the 15-min lifting task, the subjects rated the current level of fatigue with reference to the Borg’s Rate of Perceived Exertion Scale (Borg RPE 6-20) every 1 min under the guidance of the experimenter. After experiment, IPWE was evaluated on System Usability Scale (SUS) [9]. SUS consists of ten questions. A score of 0-100 can reflect the degree of acceptance of the exoskeleton by the wearer. Usually a score greater than 60 is considered acceptable for the exoskeleton product.

2.5. Data processing
All the original EMG signals are first rectified, and subjected to 20-500Hz band-pass filtering, and then a 30Hz notch filter is used to eliminate the ECG pollution in the signal. A 50Hz notch filter was used to eliminate power frequency interference. The RMS of the EMG data was calculated to determine the signal amplitude.

2.6. Statistical analysis
In the experiment, the independent variables are whether to wear the exoskeleton and the test time. The dependent variables were the RMS amplitude, oxygen consumption and Borg scale score of the four muscles. A paired t test was used to evaluate the effect of EMG on the four muscles and the difference in oxygen consumption with or without IPWE. After the K-S test, the Borg score conformed to the normal distribution, and repeated measures analysis of variance (ANOVA) was performed. All statistical analyses were performed in SPSS software, and the significance level was set to p=0.05.

3. Result

3.1. Muscle activity
During a single lifting task and a 15-min lifting task, the RMS amplitude of TES1, LES1, and LES2 were significantly reduced under the condition of wearing IPWE (p<0.05); TES2 muscle activity has only a significant difference with or without IPWE conditions in a single lifting task (Table 1). Figure 4 shows the RMS amplitude under two tasks. Muscle activity would be reduced when wearing IPWE under different tasks. During a single lifting task, IPWE reduced LES1 and LES2 muscles activity by 24.03% and 18.09%, respectively. In the 15-min lifting task, IPWE reduced LES1 and LES2 muscle
activities by 28.03% and 25.05%, respectively. It indicates that IPWE can do its work to waist muscles, and the effect is obvious. In the process of single and 15-min lifting tasks, IPWE had the least help effect on TES2 muscles, reducing muscle activity by only 10.85% and 14.63%, respectively.

Table 1. Summary of means and standard deviations of RMS amplitude for all muscles and conditions

| Muscle | Condition | Single/15min | RMS amplitude | Standard deviation | P value |
|--------|-----------|--------------|---------------|--------------------|---------|
| TES1   | Y         | single       | 19.8          | 1.9                | 0.041   |
| TES1   | N         | single       | 23.0          | 2.3                |         |
| TES1   | Y         | 15min        | 26.2          | 2.9                |         |
| TES1   | N         | 15min        | 32.4          | 3.6                | 0.023   |
| TES2   | Y         | single       | 18.9          | 1.6                |         |
| TES2   | N         | single       | 21.2          | 2.0                | 0.105   |
| TES2   | Y         | 15min        | 25.1          | 2.4                |         |
| TES2   | N         | 15min        | 29.4          | 3.0                | 0.048   |
| LES1   | Y         | single       | 35.4          | 4.1                |         |
| LES1   | N         | single       | 46.6          | 5.0                | 0.012   |
| LES1   | Y         | 15min        | 36.2          | 6.3                |         |
| LES1   | N         | 15min        | 50.3          | 7.9                |         |
| LES2   | Y         | single       | 32.6          | 3.8                | 0.035   |
| LES2   | N         | single       | 39.8          | 4.8                |         |
| LES2   | Y         | 15min        | 34.1          | 5.6                |         |
| LES2   | N         | 15min        | 45.5          | 6.9                | 0.001   |

Figure 5 shows the average relative oxygen consumption (ml/kg/min) of 8 subjects during the test with and without IPWE. Paired t-test results showed there is no significant difference in relative oxygen consumption under the two conditions (p=0.48). The average value of all subjects during the entire 15-min was 15.88 (±1.20) ml/kg/min (IPWE) and 16.02 (±1.00) ml/kg/min (NO-IPWE).

3.2. Subjective responses

3.2.1. Borg’s Rate of Perceived Exertion Scale

The Borg score under the two conditions is shown in Figure 6. After repeated measurement variance test, the Borg ratings of perceived exertion (RPE) are significantly different in time scale under 15-min with/without IPWE (p=0.047<0.05). It indicates that the score will increase significantly with time under the two conditions. There is no interaction between time and equipment to show that IPWE has affected the Borg score, and the presence/absence of IPWE will not cause a significant difference in Borg score. At the end of the 15th minute, the average Borg score under IPWE conditions was 10.80 (±0.85), which was higher than the average score of 10.10 (±0.60) under NO-IPWE conditions.

Figure 4. Mean RMS amplitude values of lumbar erector spinaes (LES1, LES2) and thoracic erector spinae (TES1, TES2) with (Y) and without (N) IPWE. (a) single lifting task; (b) 15-min lifting task.
Significant results ($p < 0.05$) are marked with an *.

Figure 5. Average Relative Oxygen Consumption of 8 subjects over time for the IPwE(Y) and No-IPwE(N) conditions.

Figure 6. Mean Borg scale ratings of 8 subjects over time for the IPwE(Y) and No-IPwE(N) conditions.

3.2.2, Local perceived pressure

The scores of all subjects’ local perceived pressure are shown in Figure 7. The average perception scores of the three parts most closely in contact with IPwE are: Thighs (2.70)$>$Shoulders (1.89)$>$Waist (1.21). The subjects felt the greatest contact pressure on the thighs, followed by the shoulders, and the lower pressure on the waist.

Figure 7. Mean local perceived pressure of 8 subjects for single lifting tasks with IPwE.
3.2.3, Usability
After the experiment, 8 subjects performed system usability rating of the exoskeleton. Systems with a score of 60 points or more are generally considered to be products with better usability. Among them, 4 subjects scored 70 points and above, which was higher than the acceptable usability standard, and the other 4 subjects scored within the acceptable threshold range.

Figure 8. Participant SUS ratings of the exoskeleton

4. Discussion

4.1. Muscle activity
The analysis of the experimental results of EMG shows that whether it is to perform a single lifting task or a 15-minute repeated lifting task, IPWE has a significant boosting effect on the low back. When performing a 15-minute task, IPWE has a better boosting effect on the low back compared with a single mission. This is basically the same as the feedback from the subjects after the experiment. Wearing IPWE will make it easier to lift heavy objects around the waist. Due to the reduction in muscle activity, it can be expected that when workers wear IPWE for bending and carrying work, the muscle fatigue of the lower back will be reduced, thereby reducing the risk of LBD.

4.2. Oxygen consumption
In the experimental results, the average relative oxygen consumption under the conditions of NO-IPWE and IPWE only differed by 0.14 ml/kg/min. It indicates that whether to wear IPWE has no effect on the oxygen consumption of subjects, that is, wearing passive exoskeleton will not significantly increase/reduce the oxygen consumption index in repetitive lifting tasks is also consistent with the conclusion drawn by Whitfield et al.

4.3. Subjective responses
After repeated measurement variance test, the Borg ratings of perceived exertion (RPE) are significantly different in time under 15min with/without IPWE (p=0.048<0.05), that is, the score will increase significantly with time under the two conditions. But there is no significant difference with/without IPWE.

When the subjects put on the IPWE for lifting tasks, the LPP score of the thigh with the greatest perceived pressure was 2.70 (±0.80). It indicates that wearing IPWE would not cause additional pain or injury to the workers. However, it should be noted that the LPP is only measured after the user performs 15 lifting tasks. As the time increases, the LPP would increase. A similar conclusion appeared in the article by Nilson et al [10]. The possible reason is that the waist elastic units and shoulder straps transfer the force of the waist to the shoulders and legs, so as to reduce waist fatigue during long-term lifting tasks. In addition, it is also possible that in the experiment the straps are too tight for the firm fixation of the leg baffles, or the force set by the Waist elastic units is too large. At
the same time, narrow shoulder straps may also be one of the reasons for the highest LPP score on the shoulder. The improvement plan of IPWE includes measures to widen the webbing and add cushions to the shoulders and thighs.

After the test, half of the subjects believed that IPWE was a product with better usability. The subjects with a usability score of less than 70 held a neutral attitude and reflected that they were wearing IPWE with a higher weight. Therefore, in subsequent research and development, weight loss of IPWE is needed to improve the acceptance of subjects.

4.4. Limitations
In order to prevent the subjects from experiencing excessive fatigue damage, this experiment only set up 15 minutes to simulate repeated lifting tasks in the working environment. After the optimized design of IPWE is completed in the future, workers will be invited to wear IPWE for actual work tasks in the actual factory, and LPP and SUS scores will be given after one week, which will help to more accurately evaluate this exoskeleton performance.

5. Conclusions
Experiments show that whether it is to perform a single lifting task or a 15-minute repetitive lifting task, IPWE significantly reduces waist muscle activity. When performing long-term repetitive lifting tasks, IPWE has the most significant help effect on lumbar erector spinaes, reducing LES1 and LES2 muscle activity by 28.03% and 25.05%, respectively. When performing a single lifting task, it reduces LES1 and LES2 muscles activity by 24.03% and 18.09%, respectively. In the process of single and 15-min lifting tasks, IPWE has the least help effect on TES2 muscles, reducing only 10.85% and 14.63% of muscle activity, respectively. In addition, the presence/absence of IPWE does not cause differences in the oxygen consumption of subjects. The results of Borg RPE showed that RPE increased significantly over time, but there was no significant difference with or without IPWE. The LPP score indicates that IPWE will additionally cause an increase in the perceived pressure on the thighs and shoulders. Among them, half of the subjects believed that IPWE had acceptable availability.

In conclusion, IPWE can significantly relieve the muscle fatigue of the lower back muscles of subjects when performing the bending and carrying task, and can reduce the risk of muscle injury of workers. However, there is no evidence that wearing IPWE can improve work efficiency or extend working hours. The discomfort and heavier weight caused by IPWE on part of the subject's contact point reduces the user's acceptance of it, and subsequent improvements will be made to address these problems.

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References
[1] Goetzel, R.Z., Hawkins, K., Ozminkowski, R.J., Wang, S. (2003). The health and productivity cost burden of the “top 10” physical and mental health conditions affecting six large U.S. employers in 1999. J. Occup. Environ. Med. 45 (1), 5-14.
[2] Marras W.S. (2000). Occupational low back disorder causation and control. Ergonomics, 43:880-902.
[3] G. B. Andersson. (1999). Epidemiological features of chronic low-back pain. The Lancet, vol. 354, no. 9178, pp. 581–585, Aug.
[4] Woolf, A., Pfleger, B. (2003). Burden of major musculoskeletal conditions. Bulletin of the World Health Organization 81, 646–656.
[5] Bos, J., Kuijer, P.P.M., Frings-Dresen, M.H.W. (2014). Definition and assessment of specific occupational demands concerning lifting, pushing and pulling based on a systematic
literature search. Occup. Environ. Med. 59, 800–806.

[6] De Looze, M.P., Bosch, T., Krause, F., Stadler, K.S., O'Sullivan, L.W., (2016). Exoskeletons for industrial application and their potential effects on physical work load. Ergonomics 59 (5), 671–681.

[7] Chen, Y.L. (2003). The effect of the tightness of abdominal belts on the determination of maximal acceptable weight of lift. International Journal of Industrial Ergonomics, 31, 111-117, doi:10.1016/s0169-8141(02)00179-8.

[8] Grinten, V.d.; M.P.; P., S.; S., K. (1992). Development of a Practical Method for Measuring Body Discomfort, 377 Advances in Industrial Ergonomics and Safety. Taylor and Francis, 4, 311-318.

[9] Bangor, A.; Kortum, P.; Miller, J. (2009). Determining what individual SUS scores mean: Adding an adjective rating scale. Journal of Usability Studies, 4, 114-123.

[10] Nilsson, A.; Vreede, K.S.; Häglund, V.; Kawamoto, H.; Sankai, Y.; Borg, J. (2014). Gait training early after stroke with a new exoskeleton-the hybrid assistive limb: a study of safety and feasibility. Journal of Neuroengineering and Rehabilitation, 11, 92-92, doi:10.1186/1743-0003-11-92.