

## Pilot Study of Powered Wearable Robot Use for Simulated Flooring Work

Akinwale Okunola<sup>1</sup>; Abiola Akanmu, Ph.D., A.M.ASCE<sup>2</sup>; Nihar Gonsalves<sup>3</sup>; Anthony Yusuf<sup>4</sup>; and Houtan Jebelli, Ph.D., A.M.ASCE<sup>5</sup>

<sup>1</sup>Myers-Lawson School of Construction, Virginia Polytechnic Institute and State Univ., Blacksburg, VA. Email: akinwale@vt.edu

<sup>2</sup>Associate Professor, Myers-Lawson School of Construction, Virginia Polytechnic Institute and State Univ., Blacksburg, VA (corresponding author). Email: abiola@vt.edu

<sup>3</sup>Myers-Lawson School of Construction, Virginia Polytechnic Institute and State Univ., Blacksburg, VA. Email: gonsnihar@vt.edu

<sup>4</sup>Myers-Lawson School of Construction, Virginia Polytechnic Institute and State Univ., Blacksburg, VA. Email: anthonyy@vt.edu

<sup>5</sup>Assistant Professor, Dept. of Architectural Engineering, Pennsylvania State Univ., University Park, PA. Email: hkj5117@psu.edu

### ABSTRACT

Work-related musculoskeletal disorders pose a significant threat to the health, safety, and retention of skilled workers in the construction industry. Construction trades, such as floor layers, perform physically demanding work involving lifting materials and maintaining awkward postures, triggering low back disorders. Active back-support exoskeletons have emerged as potential preventive technology. This paper evaluates the suitability of a commercially available active back-support exoskeleton for a simulated flooring task by assessing measures such as range of motion, perceived level of exertion, and cognitive load. No significant difference was observed in the comparison of these measures with and without the active exoskeleton. However, the use of the exoskeleton triggered slight reductions in the range of motion of the back, perceived exertion, and mental demand. These preliminary findings could motivate more studies into the design and evaluation of similar technologies for improving construction workforce health and safety.

### INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) are severe concern in the construction industry. National Institute for Occupational Safety & Health (NIOSH) described musculoskeletal disorders as soft tissue injuries that are caused by prolonged repetitive actions that affect the muscles (CDCP 2023). Overexertion from lifting, lowering and awkward postures are some of the risk factors responsible for about 30% of WMSDs among construction workers (CDCP 2023).

The back is one of the most affected body parts (CDCP 2023). Construction trades, such as floor layers, are 0.6 times more likely to experience back-related disorders compared with other trades (BLS 2017). Floor layers (i.e., construction trades who install flooring materials e.g., tiles) bend to lift materials and assume back-bending positions for about 36% of the time they spend doing their work (McGaha, Miller et al. 2014). Some of the impacts of low back disorders, include absence from work, reduced productivity, and in severe cases, permanent disability (CDCP 2023). Consequently, construction trades such as floor layers tend to retire early, thus

resulting in shortage of skilled workforce. CDCP (2023) revealed that over 130 million dollars are spent annually on hospital visits due to WMSDs, including low back disorders.

Exoskeletons, also known as wearable robots, are increasingly being perceived as ergonomic solutions to WMSDs. Exoskeletons are wearable devices that generate forces to augmented human capabilities or execution of physical activities (Toxiri, Näf et al. 2019). Exoskeletons are broadly classified into passive or active, and according to the body parts they support e.g., full body-support, shoulder-support, leg-support, and back-support (Kermavnar, de Vries et al. 2021). Unlike passive back-support exoskeletons that provide support through dampers or springs, active back-support exoskeletons use electric motors or hydraulic actuators, thus being able to provide greater support (Kermavnar, de Vries et al. 2021). This feature has sparked increasing explorations of active exoskeletons for reducing physical demands of workplaces.

Researchers are increasingly investigating the potential of active back-support exoskeletons for preventing WMSDs. Poliero, Lazzaroni et al. (2020) assessed an active back-support exoskeleton for manual material handling tasks that involved lifting and grasping. The authors identified a reduction of 10% in the range of motion of the hip and knee while using the exoskeleton. Kim, Hussain et al. (2021) designed and assessed an active back-support exoskeleton for manual material handling tasks that involves standing, lifting and lowering. The rate of exertion increased while using the exoskeleton. Bequette, Norton et al. (2020) assessed the effects of an active and passive exoskeleton for a simulated patrol task. The authors reported a higher cognitive load rating with the active than passive exoskeleton.

Despite the growing interest and awareness of the benefits of active exoskeletons in reducing workplace injuries, there are scarce empirical studies on the efficacy of technology for construction work. This is alarming given the rate of back-related injuries in the construction industry and the impact on retention of skilled workforce. This study aims to present preliminary results of an on-going pilot study of the suitability of a commercially available active back-support exoskeleton for construction work such as flooring task. This work contributes to the scarce body of knowledge by illustrating the impact of the exoskeleton on the range of motion of the back, perceived exertion of the body and cognitive load. The preliminary findings could motivate more studies into the design and evaluation of similar technologies for improving construction workforce health and safety.

## BACKGROUND

Studies have assessed active exoskeletons for tasks across different industries using measures such as range of motion (Poliero, Lazzaroni et al. 2020), perceived level of exertion (Miura, Kadone et al. 2018), and cognitive load (Bequette, Norton et al. 2020). Poliero, Lazzaroni et al. (2020) examined the suitability of an active back-support exoskeleton (XoTrunk) for manual material handling involving lifting and grasping tasks. Range of motion of the back of nine participants (n=9) were measured using inertial measurement units (IMU) while they performed the tasks. The study showed that the exoskeleton reduced the knee and hip range of motion by 10%. (Tan, Kadone et al. 2019) assessed an active back-support exoskeleton for repetitive stooping, lifting and placing tasks. Participants' (n=20) perceived fatigue and range of motion were assessed using a visual analogue scale and a motion capture system. The authors identified that the participants experienced less fatigue while using the active back-support exoskeleton. Also, the hip angles in the stoop position were significantly lower when using the exoskeleton. Poliero, Fanti et al. (2022) compared the performance of XoTrunk and a passive back-support

exoskeleton (Laevo) for static and dynamic tasks including grabbing, lifting, reaching, and placing (n=14). Usability assessment of both exoskeletons showed that the active exoskeleton was more comfortable and offered useful assistance without impeding the tasks.

Miura, Kadone et al. (2018) assessed an active back-support exoskeleton (HAL) for snow shoveling activities (n=9). The study measured the perceived rate of exertion at the back using a visual analogue scale. It was revealed that the exoskeleton significantly reduced the perceived exertion rate and improved the performance of the snow shoveling activity. Kim, Hussain et al. (2021) analyzed a customized designed active back-support exoskeleton for manual material handling tasks involving standing, lifting and lowering (n=18). The study measured muscle activities, time up-and-go test, and perceived rate of exertion. The result shows that the perceived rate of exertion increased while using the exoskeleton. Bequette, Norton et al. (2020) investigated the effects of an active exoskeleton on physical and cognitive performance in a simulated patrol task by considering passive exoskeleton and no exoskeleton conditions. NASA-TLX was used to assess the cognitive load. The participants (n=12) experienced higher cognitive load with the active exoskeleton. The aforementioned benefits and unintended consequences (e.g., increase in cognitive load) have triggered increasing investigations into the efficacy of active back-support exoskeletons for elevating low back disorders in some industry sectors. Hence this study aims to assess a commercially available active back-support exoskeleton for construction related tasks.

## METHOD

**Participants.** Eight male participants (n = 8) volunteered to participate in the study. The average age, weight, and height of the participants are 30 years  $\pm$  6, 79.8kg  $\pm$  15.8, and 1.84m  $\pm$  0.1m respectively. The participants signed the informed consent approved by the Virginia Tech Institutional Review Board (IRB).

**Equipment and data collection instruments.** The equipment and data collection instruments are described as follows: Cray X, an active back-support exoskeleton (<https://germanbionic.com/en/>) was used for this study (Figure 1). Cray X weighs 8kg and is designed to support lifting and walking efforts, and a maximum load of 30kg. The exoskeleton consists of a frame and strap pads for the legs, chest, shoulders, and waist. The frame, which has a dimension of 0.70m height by 0.6m width, has bulge packs that houses two motors. The exoskeleton is designed to assist with 3 modes: lifting and placing, bending, and walking. These modes are assisted by activating support levels ranging from 0% to 100%.

Inertial Measurement Unit (IMU) from Yostlabs (<https://yostlabs.com/>) was used to collect the range of motion data (Figure 2). The IMU uses a triaxial gyroscope, an accelerometer, and compass sensors to determine the orientation of the device relative to an absolute reference. The IMU has a rechargeable lithium battery and micro SD card storage device for storing data while the sensor is being used.

The rate of perceived exertion (RPE) was captured using a questionnaire design based on the Borg rating scale (Borg 2004). The participants provided ratings within the range of 6 to 20, where 6 represents no exertion, 7 to 8 represents extremely light exertion, 9 to 10 represents very light exertion, 11 to 12 represents light exertion, 13 to 14 represents somewhat hard exertion, 16 to 17 represents very hard exertion, 19 represents extremely hard exertion, and 20 represents maximum exertion.

NASA Task Load Index (NASA TLX) questionnaire was used to collect data on the participants' cognitive load. The questionnaire consists of six scales namely, mental demand,

physical demand, temporal demand, performance, effort, and frustration. The participants rated each scale according to their perception of their cognitive load.

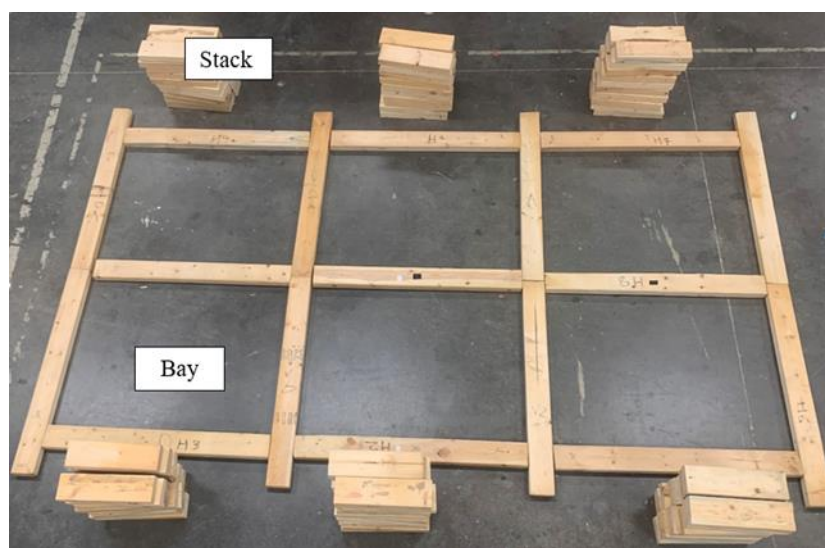


**Figure 1. Cray X.**



**Figure 2. IMU.**

**Experimental design.** The study was performed using a simulated flooring task performed in the laboratory. The task involved three subtasks: lifting, placing, and installing timber floor tiles. Each participant was instructed to lift six stacks of 20 timber tiles and place each stack beside six bays of a laboratory scale wooden frame where the tiles would be laid (as shown in Figure 3). Thereafter, the participants were asked to lay the tiles in each stack in the corresponding bay. Participants were allowed to choose any comfortable posture while performing the task. Each participant performed six cycles of the subtasks, with and without the active back-support exoskeleton.



**Figure 3. A timber frame set-up for the flooring task.**

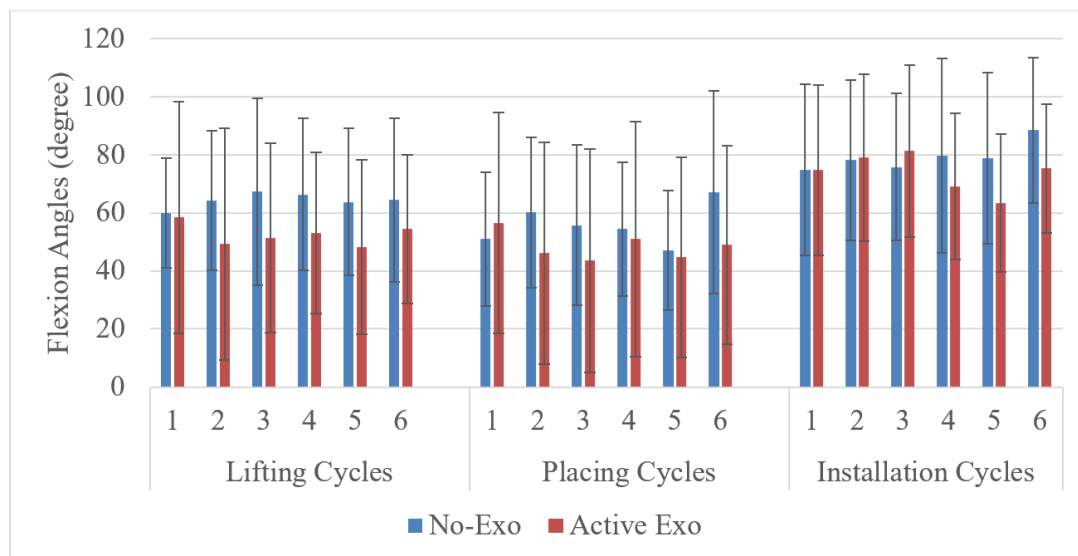
**Procedure.** Participants were given a brief introduction to the simulated flooring task and shown an example of how the task should be performed. Subsequently, they were asked to complete the task without an exoskeleton and encouraged to rest before commencing the task with the active back-support exoskeleton. During the tasks, the participants were video recorded. After completing the task without the exoskeleton, the participants were given the level of

exertion and NASA TLX questionnaires to report their experiences. Before commencing the task with the exoskeleton, the participants were introduced to the device (Cray X) and shown how it worked before being allowed to perform the task with it. They were allowed to proceed after gaining confidence with using the exoskeleton. Thereafter, the participants completed the task and subsequently filled out the questionnaires.

**Data analysis.** The range of motion data was grouped and sorted according to the task categories: lifting, placing, and installing tasks. Data analysis for range of motion, cognitive load, and perceived rate of exertion was done using descriptive statistics such as the mean score and standard deviation. The mean scores for the range of motion were compared using a 2-way analysis of variance (ANOVA). To assess statistical significant differences, the task cycles and the exoskeleton conditions (i.e., with and without exoskeleton) were considered independent variables. Before conducting the 2-way ANOVA, the range of motion dataset was tested for normality and homogeneity of variance using Shapiro-Wilk and Levene's tests respectively. Data on the cognitive load and perceived rate of exertion were also compared using Wilcoxon signed-rank test, a non-parametric statistical test.

## RESULTS

**Effect of the exoskeleton on range of motion.** After checking for the normality and homogeneity of variance ( $p > 0.05$ ) of the flexion angle dataset, 2 way-ANOVA was performed on the dataset. The test shows no significant statistical difference ( $p > 0.05$ ) between the two conditions (i.e., No-Exo and Active Exo) while considering all cycles of each subtask. However, while not significant, it is worth mentioning that besides cycle 1 (see Figure 4), there is a minimum reduction of 18% in the flexion angles during the lifting tasks, a 4% reduction during placing tasks, and a 16% reduction during installation tasks from cycle 4.



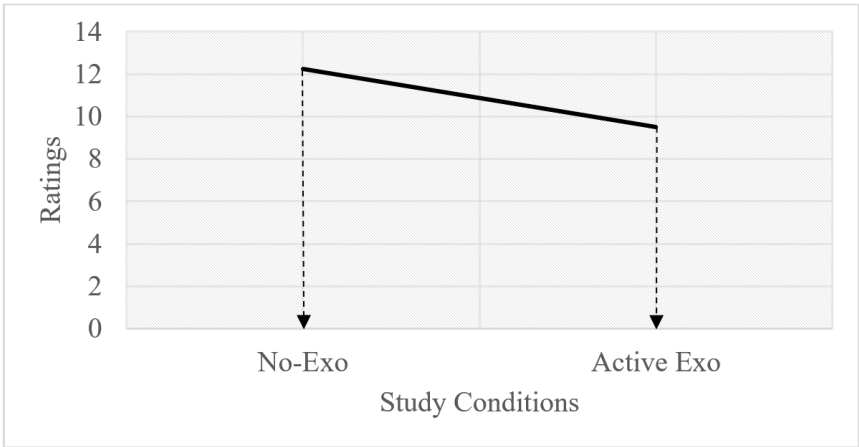
**Figure 4. Flexion angles during the lifting, placing and installation cycles.**

**Effect of the exoskeleton on perceived rate of exertion.** Table 1 and Figure 5 shows that there was a reduction of 2.75 in the perceived rate of exertion with the exoskeleton while

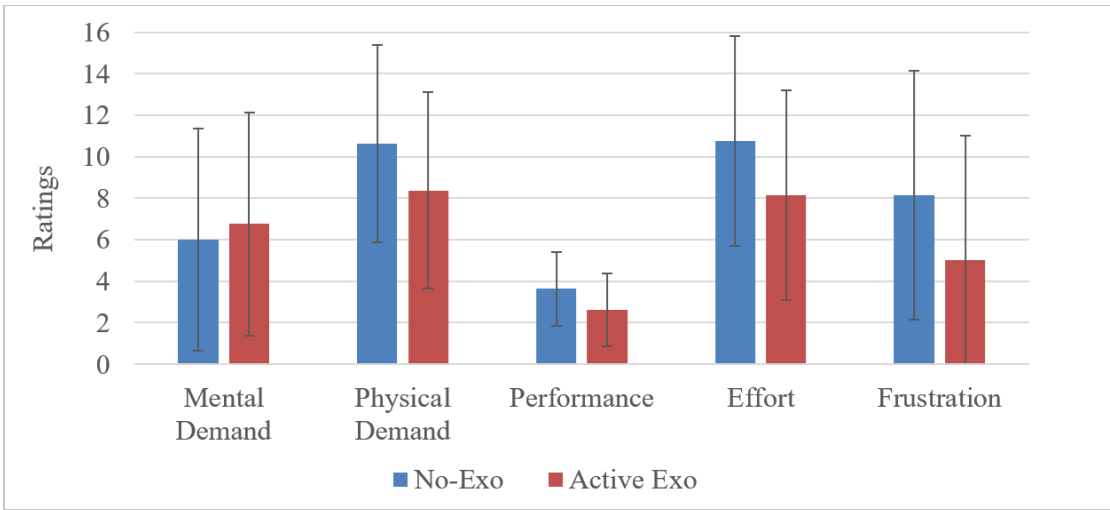
performing the flooring task. However, the Wilcoxon signed-rank test shows no significant difference ( $p > 0.05$ ) between the two conditions (i.e., No-Exo and Active Exo).

**Table 1. Change in the rate of exertion between no-exoskeleton and exoskeleton conditions.**

| Conditions | Mean   | Change | p-value |
|------------|--------|--------|---------|
| No-Exo     | 12.525 | -2.75  | 0.0793  |
| Active Exo | 9.5    |        |         |



**Figure 5. Perceived rate of exertion.**



**Figure 6. Cognitive load.**

**Effect of the exoskeleton on perceived cognitive load.** Wilcoxon signed-rank test was used to analyze five of the cognitive load scales, including mental demand, physical demand,

performance, effort, and frustration. None of the scales revealed any statistically significant difference ( $p > 0.05$ ). However, Figure 6 shows a decline in the cognitive load when using the exoskeleton i.e., 26%, 38%, 32% and 63% reductions in physical demand, performance, effort, and frustration with the exoskeleton. A higher mental demand can be observed with the exoskeleton.

## CONCLUSION, LIMITATIONS AND FUTURE WORK

The physically demanding nature of construction work exposes workers to the risks of musculoskeletal disorders. This study assessed the effect of using an active back-support exoskeleton to reduce these risks during a simulated flooring task involving eight participants. The results showed that there were no significant differences in the measures of range of motion of the back, perceived level of exertion, or cognitive load. However, some reductions were observed in range of motion and perceived exertion while using the active exoskeleton. Significant differences, in these measures, could have been observed if the sample size was larger. Other measures, such as muscle activity, heart rate, discomfort and usability, were not reported in this paper. These are important considerations that could influence the embrace of active exoskeletons in the construction industry. These are currently being investigated as part of the larger research study and will be reported when the findings are formalized. The study was conducted with novices who may not be able to accomplish tasks like experts. Therefore, caution should be exercised when applying these results to real-life situations. However, a field study is being considered as part of future research. The preliminary findings in this paper sets as a pathway for researchers and practitioners looking to explore and understand the application of an active back-support exoskeleton in the construction industry.

## ACKNOWLEDGEMENT

This material is based upon work supported by Allan Myers and the National Science Foundation under Grant No. IIS-2221167. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

## REFERENCES

- Bequette, B., A. Norton, E. Jones, and L. Stirling. (2020). "Physical and cognitive load effects due to a powered lower-body exoskeleton." *Human factors* 62(3): 411-423.
- BLS. (2017). "Injury and illness rate per 10,000 full-time workers." Retrieved March 25, 2023, from <https://data.bls.gov/pdq/SurveyOutputServlet>.
- Borg, G. (2004). "The Borg CR10 scale folder." *A method for measuring intensity of experience*. Hasselby, Sweden: Borg Perception.
- CDCP (Centers for Disease Prevention and Control). (2023). "Exoskeletons in Construction: Will they reduce or create hazards?" Retrieved March 25, 2023, from <https://blogs.cdc.gov/niosh-science-blog/2017/06/15/exoskeletons-construction/>.
- Kermavnar, T., A. W. de Vries, M. P. de Looze, and L. W. O'Sullivan. (2021). "Effects of industrial back-support exoskeletons on body loading and user experience: an updated systematic review." *Ergonomics* 64(6): 685-711.

- Kim, H. K., M. Hussain, J. Park, J. Lee, and J. W. Lee. (2021). "Analysis of Active Back-Support Exoskeleton During Manual Load-Lifting Tasks." *Journal of Medical and Biological Engineering*.
- McGaha, J., K. Miller, A. Descatha, L. Welch, B. Buchholz, B. Evanoff, and A. M. Dale. (2014). "Exploring physical exposures and identifying high-risk work tasks within the floor layer trade." *Applied ergonomics* 45(4):
- Miura, K., H. Kadone, M. Koda, T. Abe, H. Endo, H. Murakami, M. Doita, H. Kumagai, K. Nagashima, and K. Fujii. (2018). "The hybrid assisted limb (HAL) for care support, a motion assisting robot providing exoskeletal lumbar support, can potentially reduce lumbar load in repetitive snow-shoveling movements." *Journal of Clinical Neuroscience* 49: 83-86.
- Poliero, T., V. Fanti, M. Sposito, D. G. Caldwell, and C. Di Natali. (2022). Active and passive back-support exoskeletons: a comparison in static and dynamic tasks. *2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*, IEEE.
- Poliero, T., M. Lazzaroni, S. Toxiri, C. Di Natali, D. G. Caldwell, and J. Ortiz. (2020). "Applicability of an active back-support exoskeleton to carrying activities." *Frontiers in Robotics and AI* 7: 579963.
- Tan, C. K., H. Kadone, K. Miura, T. Abe, M. Koda, M. Yamazaki, Y. Sankai, and K. Suzuki. (2019). "Muscle synergies during repetitive stoop lifting with a bioelectrically-controlled lumbar support exoskeleton." *Frontiers in Human Neuroscience* 13: 142.
- Toxiri, S., M. B. Näf, M. Lazzaroni, J. Fernández, M. Sposito, T. Poliero, L. Monica, S. Anastasi, D. G. Caldwell, and J. Ortiz. (2019). "Back-support exoskeletons for occupational use: an overview of technological advances and trends." *IIEE Transactions on Occupational Ergonomics and Human Factors* 7(3-4): 237-249.