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Influence of Active Back-Support Exoskeleton on Fall Hazard in Construction

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Active back-support exoskeleton has gained recognition as a potential solution to mitigate work-related musculoskeletal disorders. However, their utilization in the construction industry can introduce unintended consequences, such as increased fall hazards. This study examines the implications of using active back-support exoskeleton on fall risk during construction framing tasks, incorporating wearable pressure insoles for data collection. Two experimental conditions were established, one involving the simulation of construction framing tasks with exoskeleton and the other without exoskeleton. These tasks encompassed six subtasks: measuring, assembly, nailing, lifting, moving, and installation. Foot plantar pressure distribution was recorded across various spatial foot regions, including the arch, toe, metatarsal, and heel. Statistical analysis, employing a paired t-test on peak plantar pressure data, revealed that the use of active back-support exoskeleton significantly increased fall risks in at least one of the foot regions for all subtasks, except for the assembly subtask. These findings provide valuable insights for construction stakeholders when making decisions regarding the adoption of active back-support exoskeleton in the industry. Moreover, they inform exoskeleton manufacturers of the need to develop adaptive and customized exoskeleton solutions tailored to the unique demands of construction sites.

Key Words: Fall hazards, Pressure insoles, Exoskeletons, Framing task, Peak plantar pressure

Introduction

Exoskeletons are gradually gaining attention across various industry sectors as solutions to work-related musculoskeletal disorders (WMSDs), which occur as a result of prolonged exposure of the body's musculoskeletal system to physically demanding tasks. Given the physically demanding nature of construction work, there are growing interests among stakeholders in the adoption of exoskeletons. Exoskeletons are wearable robotic systems designed to provide bodily support and reduce the risk of overexertion. Exoskeletons are categorized based on the specific body parts they support, including leg-support, back-support, shoulder-support, and full body-support (Poliero, Fanti, Sposito, Caldwell, & Di Natali, 2022). Depending on the source of support, exoskeletons further classified as active or passive (Poliero et al., 2022). While passive exoskeletons lack motorized components for generating body support, active exoskeletons are equipped with electrical or pneumatic mechanisms to provide support (Poliero et al., 2022). Research has highlighted the promise of active back-support exoskeletons in various assessments, including findings such as decreased range of motion (Poliero et al., 2020), reduced muscle activity (Reimeir, Calisti, Mittermeier, Ralfs, & Weidner, 2023), diminished perceived exertion (Walter, Stutzig, & Siebert, 2023), and mitigated discomfort (Huysamen et al., 2018). However, alongside these benefits, research has also unveiled unintended consequences associated with back-support exoskeletons that can pose fall hazards. For instance, Huysamen et al. (2018) investigated the use of active back-support exoskeleton (aBSE) in manual material handling, highlighting its potential to exert pressure on the body, thereby raising concerns about fall hazards, particularly when working at elevated heights. Alemi, Madinei, Kim, Srinivasan, and Nussbaum (2020) conducted a comparative analysis of two passive back-support exoskeletons during repetitive lifting task. Their research underscored how improper anthropometric fit of exoskeletons could impede body mobility and contribute to fall hazards. Additionally, Fox, Aranko, Heilala, and Vahala (2019) conducted a review of the adverse effects of passive back-support exoskeletons, emphasizing that the additional weight of these devices may disrupt the body's center of gravity and result in balance issues. The same could be said of active exoskeletons which weigh more than passive exoskeletons.

Fall risk in construction-related tasks has been evaluated using pressure insole wearable sensors. The sensors have the ability to directly assess fall risk based on foot distributions. For example, Antwi-Afari and Li (2018) examined fall hazards in construction scenarios involving loss of balance events, such as slips, trips, unexpected step-downs, and twisted ankles, utilizing plantar pressure data from pressure insoles. Their study focused on evaluating peak pressure in four specific spatial foot regions across all these events, underscoring the effectiveness of using pressure insoles to assess fall risk in construction work. Despite this evidence, scarce studies have assessed the risk of fall hazards while using exoskeletons for construction work. The construction sector is rife with diverse, high-risk working conditions, including tasks at elevated heights, on uneven surfaces, and in unpredictable weather conditions, all of which may exacerbate fall hazards when exoskeletons are employed. Notably, active back-support exoskeletons, with their substantial weight and bulk, pose a potential risk of increasing fall hazards when used on construction sites.

Therefore, this study aims to investigate the impact of aBSE on fall hazards in construction, using carpentry tasks as a case study. The findings from this research can serve to inform exoskeleton manufacturers interested in deploying their products for construction applications. It underscores the need for adaptive exoskeleton solutions tailored to the specific challenges posed by construction sites.

Background

Triggers of Fall Risk in Exoskeleton Usage

In recent years, studies have investigated the unintended consequences associated with exoskeleton use, which may result in fall hazards across a range of industrial domains. These unintended consequences include disparities in load distribution on to the body (Weston, Alizadeh, Knapik, Wang, & Marras, 2018), reported discomfort in the body parts (Gonsalves, Ogunseiju, Akanmu, & Nnaji, 2021), risks of entanglement and snagging (Kim et al., 2019), and as well as restriction in movement (Ogunseiju, Gonsalves, Akanmu, & Nnaji, 2021). For example, Weston et al. (2018) examined the impact of passive postural-assist exoskeleton on the spine during manual material handling tasks. The study revealed increased load on the spine which could alter the gait of the body and lead to fall hazards. Gonsalves et al. (2021) assessed the efficacy of passive back-support exoskeletons for rebar work that involves placing and tying subtasks. The study demonstrated that the use of the exoskeleton inflicted pain on the participants which significantly caused discomfort in the chest region. Kim et al. (2019) assessed the potential of passive exoskeletons for the construction industry by conducting semi-structured interviews with industry stakeholders. Their research highlighted that concerns related to catch and snag risks emerged as prominent barriers to exoskeleton adoption, with the potential to increase fall hazards. Ogunseiju et al. (2021) investigated the effectiveness of passive back-support exoskeletons in a construction floor laying task. Their findings indicated that the exoskeletons hindered users' movements and disrupted their work processes, potentially contributing to fall hazards.

Wearable Sensors for Evaluating Fall Risks

Studies have explored the use of wearable sensors for assessing fall hazards across various sectors and during different events. Gait metrics extracted from inertial measurement unit (IMU) (Jebelli, Ahn, & Stentz, 2016; Liu, Zhang, & Lockhart, 2012) and pressure insoles (Antwi-Afari & Li, 2018; Mickle, Munro, Lord, Menz, & Steele, 2010; Yan et al., 2023) have been employed to evaluate fall risks. For instance, Liu et al. (2012) investigated fall hazards among three groups – healthy young, healthy old, and fall prone old – during a tread mill activity using IMU. They extracted acceleration, maximum Lyapunov exponent, and center of pressure metrics from the anterior-posterior, medio-lateral, and vertical directions of the foot based on IMU data. Jebelli et al. (2016) evaluated the fall risk of construction ironworkers while performing four different tasks, which involved standing and squatting while bearing varying symmetrical and asymmetrical loads. They utilized IMUs attached to the waist and a force plate to capture gait data, where kinematic metrics were extracted to compute the center of pressure and acceleration for fall risk assessment. While research has explored the appropriateness of IMU for assessing fall risks, the notable shortfall lies in the ability to evaluate fall risk through distributed pressures across the foot region.

Pressure insoles have been adopted to assess fall risk using foot plantar pressure metrics that show greater sensitivity to gait changes across the foot region (Antwi-Afari & Li, 2018). Specifically, higher peak pressure could disrupt balance and stability and lead to fall hazards Yan et al. (2023) (Mickle et al., 2010). Recently, studies have examined the use of peak pressure metric of the foot plantar pressure for the assessment of fall risk for elderly people (Mickle et al., 2010; Yan et al., 2023) and construction workers (Antwi-Afari & Li, 2018). For instance, Mickle et al. (2010) conducted a fall risk assessment among older individuals classified as fallers and non-fallers during a walking task. Foot plantar pressure distribution was recorded for all foot regions using force plates. The study revealed significantly higher peak pressure among the fallers, with the heel, metatarsal, and toe regions of the foot showing significantly elevated peak pressure. Yan et al. (2023) assessed fall hazards in older individuals categorized as low-risk and high-risk for falls, utilizing pressure insoles during a walking task. The foot plantar pressure distribution was captured for all foot regions, divided into eight sections. The results indicated no statistical significance between the two groups, but the heel and midfoot regions exhibited higher pressure. Antwi-Afari and Li (2018) evaluated the fall risk of construction workers during loss of balance events, encompassing scenarios such as slips, trips, unexpected step-downs, and twisted ankles. Foot plantar pressure distribution was recorded using pressure insoles for all foot regions, and peak pressure was computed. The results revealed the differences in the loss of balance events compared to the control experiment. When considering the use of aBSEs, several factors emerge that could potentially increase fall hazards. Their use in the construction industry could elevate fall risk due to repetitive abnormal postures, working on uneven surfaces, and exposure to uncontrolled atmospheric conditions. However, there remains a scarcity of studies that have specifically examined the fall risk of aBSE users engaged in construction-related tasks.

Method

This section illustrates the methods adopted in this study. As described in Figure 1 below, the method discussed the participants, instruments and data collection, experimental procedures, data processing and analysis.

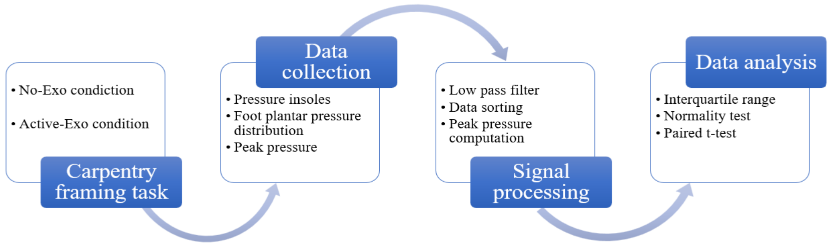

Figure 1. Methods overview.

Participants

Sixteen healthy students with no previous reported history of musculoskeletal disorders were recruited for this study. Participants are male with the following demographic features in mean and standard deviation: age – 30 (4) years, stature – 173 (5.5) cm, body weight – 72 (7.5) kg, and body mass index – 23.98 (1.9) kg/m^2. This study was conducted with approval of the Virginia Tech Institutional Regulatory Board (IRB: 19-796). Informal consent was obtained from all the participants before proceeding with the experiment.

Instruments and Data Collection

This section provides an overview of the exoskeleton and data acquisition technologies utilized in the experimental study, elucidating their roles in the data collection process.

Exoskeleton

The aBSE adopted for this experiment is CrayX, which was designed by German Bionic, and weighs approximately 7.5kg (Figure 2a). The device has three major assistive modes of operation that help to support the user's body during tasks involving lifting, placing, and walking. The assistive modes can be adjusted from 0 to 100%, depending on the level of support required. The aBSE is designed to be worn as a backpack and strapped to the body.

Pressure Insole

The plantar pressure distributions of the foot regions were captured using Moticon Opengo's pressure insole at a sampling rate of 100 Hz. As shown in Figure 2b, the pressure insole consists of a pair of insoles, i.e., for the right and left foot. Each insole consists of 16 sensors distributed across the foot regions. Sensors 1-4, 5–8, 9–13, and 14–16 capture the heel, the arch, the metatarsal and the toe regions, respectively (Figure 2b). Based on evidence from existing literature (see Background section), this study focused on computing the peak plantar pressure across the foot regions in a construction framing task.

Figure 2. Instruments: (a) CrayX (Source: German-Bionic, 2023); (b) Distribution of pressure insoles across foot regions. (Source: Moticon-OpenGO, 2023)

Experimental Procedure

A carpentry framing task was repeatedly simulated, comparing two distinct conditions: one without an exoskeleton (No-Exo) and the other with an active exoskeleton (Active-Exo) (Figure 3). This framing task required all the participants to complete six sequences of subtasks, including measuring, assembly, nailing, lifting, moving, and installation. The duration of each experimental condition did not exceed five minutes to mitigate the potential influence of fatigue (Antwi-Afari et al., 2021). The sequential design of the experiment ensured the practical replication of the complete framing task. Also, the participants were allowed to rest for 30 minutes after completing the first experimental condition (No-Exo) before proceeding to the second condition (Active-Exo condition) (Antwi-Afari et al., 2021). While engaged in these experimental conditions, participants wore pressure insoles to capture the distribution of plantar pressure on their feet. The independent variables in this study encompassed the two experimental conditions, while the dependent variable pertained to the various foot regions and peak pressure in the plantar pressure distribution of the foot. The experiment began with an orientation for participants, outlining the objective of the study, which was to gather data for assessing fall risks during framing tasks with and without an aBSE. Before commencing the experiment, the participants were briefed on the functionality of the exoskeleton and had the opportunity to practically explore its features. Subsequently, pressure insoles were inserted into their shoes. Participants were presented with a model of a typical frame that they were expected to replicate. The task commenced with participants measuring the supplied timber logs, comprising four pieces with a length of 1.8m and two pieces with a length of 1.2m, all having a cross-sectional area of 100mm x 25mm. Next, they assembled the measured timbers in accordance with the provided model. Subsequently, participants utilized a nail gun to secure the assembled timber together during the nailing subtask. Finally, participants manually lifted the frame and transported it to an upper floor through a staircase for installation (see Figure 3).

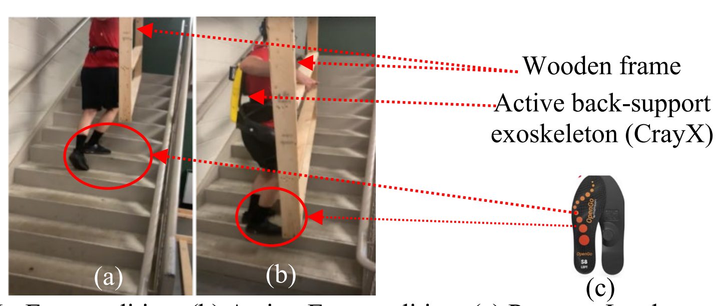

Figure 3. Framing task: (a) No-Exo condition; (b) Active-Exo condition; (c) Pressure Insoles.

Data Processing and Analysis

Physiological sensing technologies face susceptibility to artifacts, particularly when utilized in tasks encompassing body movements and the presence of electromagnetic devices in the surroundings. Given the context of this study involving carpentry framing tasks, the collected data underwent a 12th order Butterworth low-pass filtering with an 8 Hz cutoff frequency Price (2018). This was followed by sorting the filtered data according to the subtasks. For each of the foot regions, the peak plantar pressure was computed using the data from the right and left foot sensors. The filtering and computation were carried out in MATLAB 2023Ra. The foot plantar pressure, recorded through the pressure insole, constitutes continuous data. Consequently, the dataset underwent screening using the interquartile range to establish the lower limit (Q1 - 1.5 * IQR) and upper limit (Q3 + 1.5 * IQR) for the removal of potential outliers. Subsequently, a normality test (Shapiro-Wilk) was applied to discern the data's distribution, guiding the choice of appropriate statistical analysis. Having passed the normality test, a paired t-test was employed to assess the statistical distinctions between the experimental conditions, namely No-Exo and Active-Exo. This analysis was conducted across all six subtasks considered in the study. The outcomes were visually represented through bar graphs, which also conveyed the associated statistical significance. scholarUP1#

Results

Measuring Subtask

Figure 4a illustrates the results of the two experimental conditions compared in this study for the measuring subtask. The result shows that the peak plantar pressure was significantly ($P < 0.05$) higher across the entire spatial foot regions while using aBSE. The peak plantar pressure increased by 16%, 10%, 23%, and 12% across the arch, heel, metatarsal, and toe regions, respectively.

Assembly Subtask

Figure 4b shows that there is no statistical significance ($P > 0.05$) between the peak plantar pressure of No-Exo and Active-Exo conditions across the entire foot region. However, there was a slight increment of 8%, 6%, and 3% in the peak pressure in regions of the arch, metatarsal, and toe, respectively.

Nailing Subtask

As depicted by Figure 4c, there was a significant difference ($P < 0.05$) in the peak plantar pressure of the foot regions of the arch, metatarsal, and toe with an increment of 8%, 13, and 10%, respectively, during the Active-Exo condition in the nailing subtask. The heel region also shows an increase of 2% in the peak plantar pressure; however, it is not statistically significant ($P > 0.05$).

Lifting Subtask

The lifting subtask is represented by Figure 4d, which shows that the use of aBSE significantly increases ($P < 0.05$) the peak plantar pressure across the entire foot regions of arch, heel, metatarsal, and toe by 20%, 11%, 38%, and 24%, respectively.

Moving Subtask

Figure 4e shows the outcome of the two experimental conditions while moving the frame. The results show that only the peak plantar pressure of the heel region is significantly ($P < 0.05$) higher while using the aBSE, with an increase of 15%. However, there was a slight increase in the peak plantar pressure of the arch and toe regions of the foot, with an increase of 1 and 3%, respectively.

Installation Subtask

The installation subtask is represented in Figure 4f. The result shows that the Active-Exo conditions show a higher peak plantar pressure of 20%, 11%, 38%, and 23% across all the entire foot regions of the arch, heel, metatarsal, and toe, respectively.

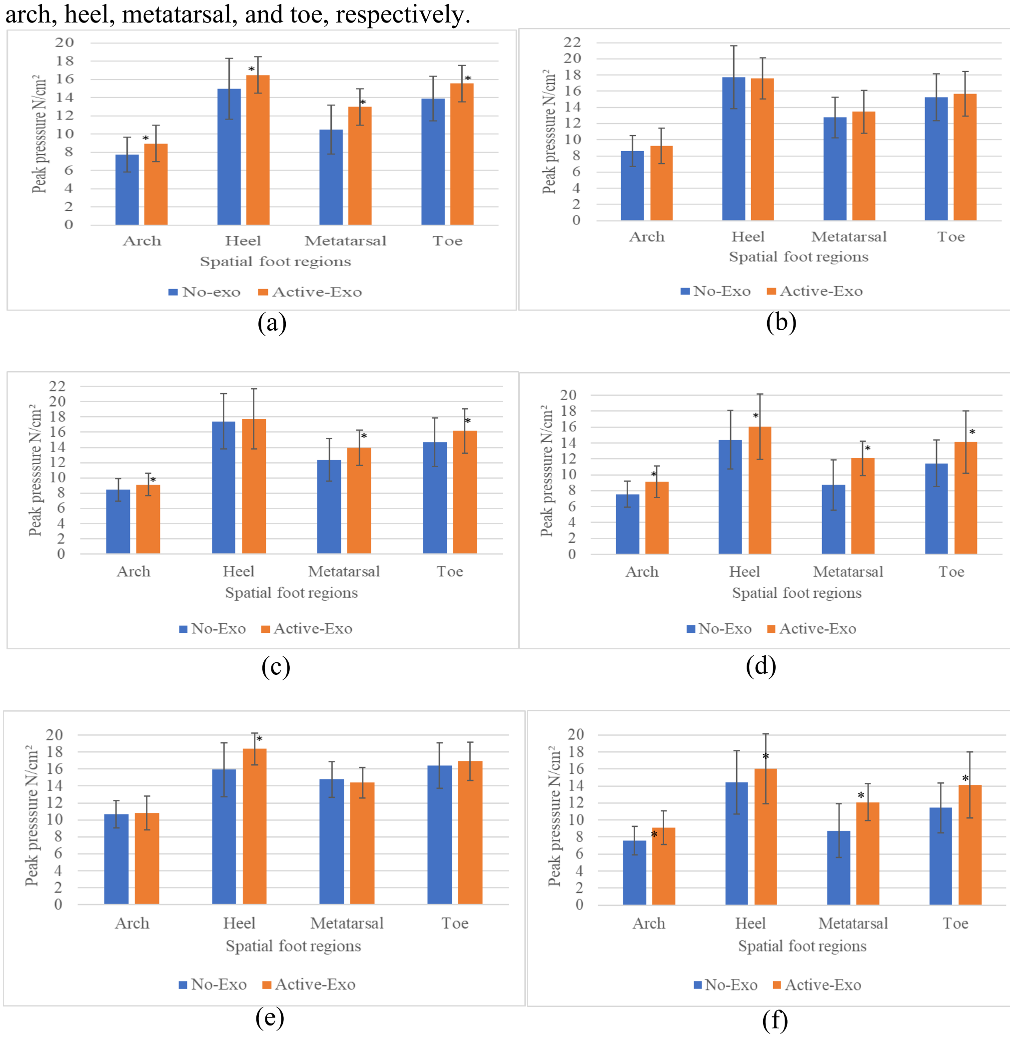

Figure 4. Peak plantar pressure: (a) measuring subtask, (b) assembly subtask, (c) nailing subtask, (d) lifting subtask, (e) moving subtask (f) installation subtask.
(“*” = significant at p-value < 0.05)

Conclusion, Limitations, and Future work

In anticipation of adopting aBSE in the construction industry to combat WMSDs, this study evaluates the risk of fall while using aBSE for construction framing task. Fall risk was captured using pressure insoles wearable sensors. The construction framing task was simulated across six subtasks, such as measuring, assembly, nailing, lifting, moving, and installing, where the foot plantar pressure distribution was captured across the entire foot regions in two experimental conditions. By comparing the peak plantar pressures of the two experimental conditions, the results showed that the use of aBSE significantly increased the peak plantar pressure across all the subtasks except during the assembly subtask. The significant increases in peak plantar pressure imply an increase in fall risk while using the aBSE. This study has the following limitations: The foot plantar pressure data underwent low-pass filtering at a frequency of 8 Hz which may not be optimal for data processing. This study was conducted in a laboratory setting with novices who had limited practical knowledge of carpentry tasks; this may affect the output of the results. While this study has been conducted for carpentry framing task, the results may not generalize across other construction tasks due to the differences in motion and postures inherent in every task. Future studies would consider evaluating the fall risk of actual construction workers performing work on construction sites, especially tasks involving work at height such as roofing and masonry. Also, future study would consider filtering the data at a lower frequency. While this study reported only findings on foot plantar pressure distribution, results of other indicators such as pressure-time integrals, pressure gradient, full width at half maximum, and average pressure could help better understand the impact of aBSE on fall risk. This study unveils the unintended consequence of increase in fall risk due to aBSE use in construction industry, despite its biomechanical advantages to reduce WMSDs. This study contributes to the scare body of knowledge assessing the ergonomic risk of using aBSE in the construction industry.

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References

Alemi, M. M., Madinei, S., Kim, S., Srinivasan, D., & Nussbaum, M. A. (2020). Effects of two passive back-support exoskeletons on muscle activity, energy expenditure, and subjective assessments during repetitive lifting. *Human factors, 62*(3), 458-474. DOI:10.1177/0018720819897669

Antwi-Afari, M. F., & Li, H. (2018). Fall risk assessment of construction workers based on biomechanical gait stability parameters using wearable insole pressure system. *Advanced Engineering Informatics, 38*, 683-694. DOI:10.10.16/j.aei.2018.10.002

Antwi-Afari, M. F., Li, H., Anwer, S., Li, D., Yu, Y., Mi, H. Y., & Wuni, I. Y. (2021). Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers. *Safety science*, 142, 105382.DOI: 10.1016/j.ssci.2021.105382

Fox, S., Aranko, O., Heilala, J., & Vahala, P. (2019). Exoskeletons: Comprehensive, comparative and critical analyses of their potential to improve manufacturing performance. *Journal of*

Manufacturing Technology Management, 31(6), 1261-1280. DOI:10.1108/JMTM-01-2019-0023

German-Bionic (2023). *CrayX* [Online]. Available: https://germanbionic.com/en/solutions/exoskeletons/crayx/ [Accessed December, 8 2023]

Gonsalves, N. J., Ogunseiju, O. O., Akanmu, A. A., & Nnaji, C. A. (2021). Assessment of a passive wearable robot for reducing low back disorders during rebar work. *J. Inf. Technol. Constr., 26*(2021), 936-952. DOI:10.36680/j.itcon.2021.050

Huysamen, K., de Looze, M., Bosch, T., Ortiz, J., Toxiri, S., & O'Sullivan, L. W. (2018). Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks. *Applied Ergonomics, 68*, 125-131. DOI:10.1016/j.apergo.2017.11.004

Jebelli, H., Ahn, C. R., & Stentz, T. L. (2016). Fall risk analysis of construction workers using inertial measurement units: Validating the usefulness of the postural stability metrics in construction. *Safety science, 84*, 161-170. DOI:10.1016/j.ssci.2015.12.012

Kim, S., Moore, A., Srinivasan, D., Akanmu, A., Barr, A., Harris-Adamson, C., . . . Nussbaum, M. A. (2019). Potential of exoskeleton technologies to enhance safety, health, and performance in construction: Industry perspectives and future research directions. *IISE Transactions on Occupational Ergonomics and Human Factors, 7*(3-4), 185-191. DOI:10.1089/24725838.2018.156157

Liu, J., Zhang, X., & Lockhart, T. E. (2012). Fall risk assessments based on postural and dynamic stability using inertial measurement unit. *Safety and health at work, 3*(3), 192-198. DOI: 10.5491/SHAW.2012.3.3.192

Mickle, K. J., Munro, B. J., Lord, S. R., Menz, H. B., & Steele, J. R. (2010). Foot pain, plantar pressures, and falls in older people: a prospective study. *Journal of the American Geriatrics Society, 58*(10), 1936-1940. DOI:10.1111/j.15532-5415.2010.03061.x

Moticon-OpenGo (2023). *OpenGo sensor insoles* [Online]. Available: https://moticon.com/opengo/sensor-insoles [Accessed 12/03/2023 2023]

Ogunseiju, O., Gonsalves, N., Akanmu, A., & Nnaji, C. (2021). Subjective Evaluation of Passive Back-Support Exoskeleton for Flooring Work. *EPiC Series in Built Environment, 2*, 10-17. https://6login.easychair.org/publications/download/P3d5

Poliero, T., Fanti, V., Sposito, M., Caldwell, D. G., & Di Natali, C. (2022). Active and passive back-support exoskeletons: a comparison in static and dynamic tasks. *IEEE Robotics and Automation Letters, 7*(3), 8463-8470. DOI:10.1109/LRA.2022.3188439

Poliero, T., Lazzaroni, M., Toxiri, S., Di Natali, C., Caldwell, D. G., & Ortiz, J. (2020). Applicability of an active back-support exoskeleton to carrying activities. *Frontiers in Robotics and AI, 7*, 579963. DOI:10.3389/frobt.2020.579963

Price, F. T. (2018). *Validation of a wearable sensor insole device for analysis of postural control.* Miami University, http://rave.ohiolink.edu/etdc/view?acc_num=miami152517168199145

Reimeir, B., Calisti, M., Mittermeier, R., Ralfs, L., & Weidner, R. (2023). Effects of back-support exoskeletons with different functional mechanisms on trunk muscle activity and kinematics. *Wearable Technologies, 4*, e12. DOI:10.1017/wtc.2023.5

Walter, T., Stutzig, N., & Siebert, T. (2023). Active exoskeleton reduces erector spinae muscle activity during lifting. *Frontiers in Bioengineering and Biotechnology, 11*, 1143926. DOI:10.3389/fbioe.20231143926

Weston, E. B., Alizadeh, M., Knapik, G. G., Wang, X., & Marras, W. S. (2018). Biomechanical evaluation of exoskeleton use on loading of the lumbar spine. *Applied ergonomics, 68*, 101-108. DOI:10.1016/j.aperg.2017.11.006

Yan, Y., Ou, J., Shi, H., Sun, C., Shen, L., Song, Z., . . . Chen, Z. (2023). Plantar pressure and falling risk in older individuals: a cross-sectional study. *Journal of foot and ankle research, 16*(1), 1-11. DOI:10.1186/s13047-023-00612-4