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Framework for Quantifying the Impact of Exoskeleton on Musculoskeletal Disorder Risk Reduction

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Abstract: Construction is a labor-intensive industry requiring extensive manual handling, repeated hand motion, and exerting force. These attributes put workers at risk for Distal Upper Extremity Disorders (DUED), such as occupational wrist tendinosis, trigger finger, and carpal tunnel syndrome. Although some studies have assessed the potential impact of exoskeletons on muscle activation, these studies failed to evaluate the direct effect of exoskeletons on DUED. Therefore, the present study aims to characterize the process for directly assessing the impact of exoskeleton on DUED and evaluate the efficacy of an exoskeleton in reducing the occurrence of DUED. Relying on the Hand Activity Level Threshold Limit Value process developed by the American Conference of Governmental Industrial Hygienists, the researchers developed a framework for assessing the DUED risk associated with hand-related tasks. This study presents a framework for conducting ergonomic risk assessments and the use of intervention in the construction industry. In addition, the study provides critical insight into using a DUED-based risk assessment tool for exoskeleton evaluation research. Practitioners and researchers can determine the true cost-benefit of using an exoskeleton as a safety intervention using the risk outcome from the proposed risk assessment process.

Keywords: Exoskeleton, Musculoskeletal disorder, Repetitive motion, Risk assessment, ACGIH guidelines.

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1. Introduction

The prevalence of Work Musculoskeletal Disorders (WMSDs), also known as repetitive strain injuries, is a significant concern across industries worldwide. European studies have found that approximately 30% of workers experience muscular pain in their hands and wrists, while three out of five individuals reported WMSDs in their back, upper arms, or hands/wrists (European Agency for Safety and Health at Work, 2019). In the United States, there were 77,800 cases of upper extremity WMSDs resulting in days away from work in 2020, with hand and wrist injuries accounting for 25% of reported cases (Bureau of Labor and Statistics, 2022). These disorders lead to extended worker absences, reduced productivity, and high treatment costs (Shahid, 2017). Distal Upper Extremity Disorders (DUED), such as occupational wrist tendinosis, trigger finger, ulnar tunnel syndrome, bursitis in the wrist, and carpal tunnel syndrome, are often caused or aggravated by work methods (Antonucci, 2019). These disorders develop gradually over time due to over-exertion, awkward postures, and repetitive tasks like hammering, wrenching, and manual handling of vibrating tools (Antonucci, 2019). While some administrative controls can help reduce the impact of DUEDs, there is still room for significant improvement (So et al., 2022). Recently, researchers have explored the potential of exoskeletons in mitigating WMSD risks in occupational settings (Zhu et al., 2021)

Exoskeletons are wearable robotic devices worn by individuals to reduce physical strain while performing tasks (Kim et al., 2018). They fall into categories such as arm/shoulder support, back support, leg support, full-body assist, and hand support, and can be active, passive, or pseudo-passive (Zhu et al., 2021). Exoskeletons have been tested for their effectiveness in preventing or reducing WMSDs in various work settings, offering benefits such as increased rest times, improved completion times, and increased endurance (Antwi-Afari et al., 2021; Bock et al., 2012; Gonsalves et al., 2021). However, previous studies have not thoroughly assessed the physical demands on the distal upper extremities and the level of risk reduction provided by exoskeletons, making it challenging to fully understand the complex relationship between exoskeleton use and DUED risk reduction (Antwi-Afari et al., 2021; Hassan et al., 2022). Exoskeletons are increasingly used in construction (Zhu et al., 2021), and it is crucial to assess their impact on workers' upper extremities to ensure safety limits are not exceeded. This study aims to develop a conceptual framework for assessing the risk of DUEDs associated with hand-related tasks, specifically focusing on the use of exoskeletons. The research questions addressed are: (1) What is the process for directly assessing the impact of an exoskeleton on DUEDs? (2) What is the process for evaluating the effectiveness of an exoskeleton in reducing DUED occurrence? To the best of the authors' knowledge, no previous study has utilized the Hand Activity Level – Threshold Limit Value (HAL-TLV) method specifically for evaluating DUED risk associated with exoskeleton use in construction tasks. By incorporating the HAL-TLV method into our framework, we offer a novel approach that addresses this research gap. The framework takes into account the specific context of construction work, considering the diverse worker population and the range of construction tasks performed with wearable exoskeletons. This comprehensive approach provides a deeper understanding of the potential impact of exoskeletons on DUEDs in the construction industry and offers a structured method for evaluating and mitigating these risks. The process outlined in this framework has the potential to lead to the development of more effective interventions and strategies for reducing DUED risks among construction workers.

1.1. Exoskeleton Assessment in Construction Research

WMSDs are prevalent among construction workers, and exoskeletons have emerged as a promising solution (Zhu et al., 2021). However, previous studies on exoskeletons have not fully considered certain critical factors. For instance, Alabdulkarim et al. (2019) compared three exoskeleton designs for physical demand and quality during an overhead, repetitive drilling task with 12 participants. They found that higher precision demands increased muscle activation levels and negatively impacted quality across exoskeleton designs. Kim et al. (2018) assessed the benefits and challenges of a passive upper extremity exoskeletal vest during repetitive drilling and light assembly, discovering that it reduced the range of motion in shoulder flexion and abduction. Van Engelhoven et al. (2019) investigated the effects of Peak Torque Amplitude (PTA) provided by a passive shoulder-support exoskeleton and found that it reduced muscle activity in the bilateral shoulder flexor muscles during sustained and repetitive overhead tasks. Muscle activation reduction ranged up to 81%, and participants reported decreased perceived exertion while using the exoskeleton. However, these studies, along with others reviewed by Zhu et al. (2021), primarily focused on repetitive and/or static hand tasks without considering the Hand Activity Level (HAL), which measures the movement and effort required for a specific task (Harris et al., 2021). They also did not compare muscle activation to a threshold limit value (TLV) to determine if the level of muscle activation with the exoskeleton was within a safe range. Furthermore, while the tasks involved repetitive hand movements, these studies mainly focused on shoulder and trunk muscles and did not assess the risk of WMSDs in the distal upper extremities. Therefore, further investigation is needed to better understand the impact of exoskeletons on DUEDs, including a holistic assessment of exoskeletons that integrates TLVs into the assessment process.

1.2. Threshold Limit Values (TLVs) for Hand Activity Levels (HAL)

In 2001, the American Conference of Governmental Industrial Hygienists (ACGIH) adopted the Threshold Limit Values (TLVs) for Hand Activity Levels (HAL) to protect workers from physical agents and hand activities (Bernard and ACGIH, 2002). Occupational hygienists utilize this TLV to offer guidance and recommendations to workers engaged in manual handling tasks (Drinkaus et al., 2005). Specifically, it assesses the exposure of the hand and wrist to physical stressors in the workplace, considering factors such as force exertions, repetition, and awkward postures for mono-task jobs lasting more than four hours per day (Harris et al., 2021; Hassan et al., 2022). The ACGIH® HAL-TLV has been employed in various studies to evaluate the risk of developing musculoskeletal disorders, particularly carpal tunnel syndrome (CTS), in the hand-wrist system and to propose preventive interventions. Kapellusch et al. (2014) found that workers who exceeded the HAL-TLV exposure limit had a higher risk of developing CTS, although no additional increase in risk was observed for workers who exceeded the TLV. Bonfiglioli et al. (2013) also identified a dose-response relationship between ACGIH TLV© classification and CTS risk. Albers et al. (2004) used the ACGIH® HAL-TLV® in an ergonomic assessment of concrete screeding techniques and recommended the use of powered screeding equipment to minimize the risk of musculoskeletal injuries.

Despite the application of ACGIH HAL-TLV in industries characterized by manual hand work, such as agriculture and manufacturing (Hassan et al., 2022), its implementation in the construction industry remains understudied. Therefore, there is a need to develop a framework that can assist researchers and practitioners in evaluating exoskeletons within this context.

2. Conceptual Framework

The researchers propose a conceptual framework for managing workers' exposure to DUED (Distal Upper Extremity Disorders) during construction tasks. This framework offers a comprehensive approach to assess the effectiveness of ergonomic interventions, including exoskeletons, in construction operations. Fig. 1 illustrates the components of this conceptual framework, which incorporates HAL (Hand Activity Level) and TLV (Threshold Limit Value) risk assessment as crucial steps in the evaluation process, along with outcome measurements. The development of this framework involved gathering information from existing grey literature and academic sources related to the evaluation of exoskeletons and DUED assessment.

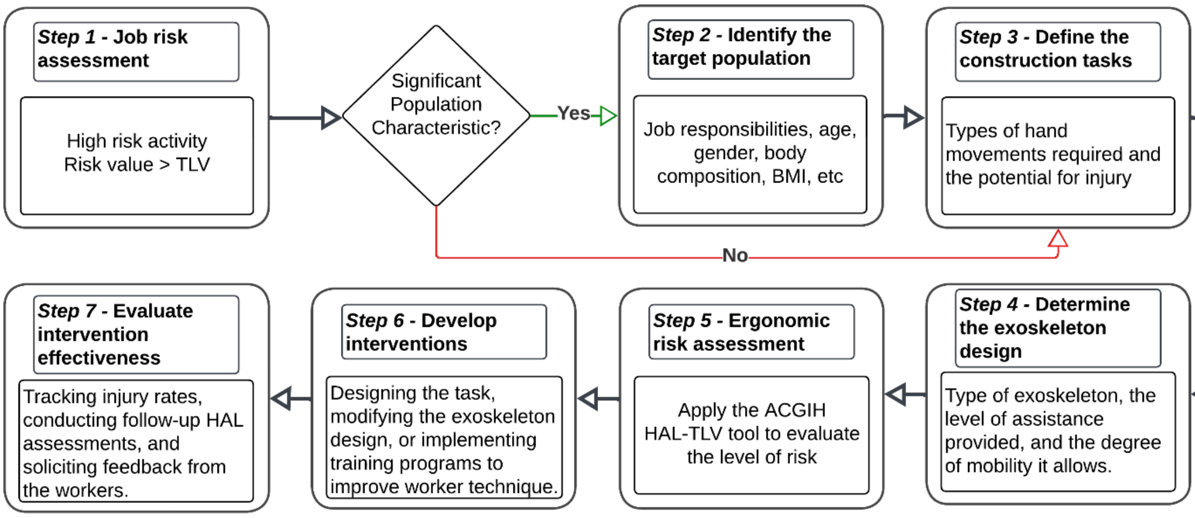

Fig. 1. Conceptual framework

The conceptual framework consists of seven steps, and they are explained below:

Step 1 – Job Risk Assessment

Step one is centered on assessing the level of risk associated with the construction task itself. Conducting this assessment helps determine if the construction task poses a high risk of DUED and/or qualifies as a high-risk activity exceeding the TLV set by the ACGIH. If the task is found to exceed the TLV and/or poses a high risk of DUED, it becomes essential to proceed with the other steps in the framework to effectively address ergonomic risks and enhance worker safety. Also, if the target population characteristic significantly influences the risk value, proceed to step 2; otherwise, proceed to step 3.

Step 2 – Identify Target Population

This step involves identifying the population that will utilize the exoskeleton, considering factors such as age, gender, body composition, aerobic activity, and job responsibilities (Søraa and Fosch-Villaronga, 2020) that may impact hand activity levels. It helps prevent unnecessary strain or injury to workers who may not require exoskeletons or may be unsuitable for wearing them.

Step 3 – Define Task

The third step is to define the construction tasks that workers will perform while using the exoskeleton. This provides a better understanding of the necessary hand movements, postures, and forces that may lead to injury.

Step 4 – Determine Appropriate Intervention Design (e.g., Exoskeleton)

The design and fit of the intervention, an exoskeleton in this case, play a crucial role in reducing ergonomic risks and preventing DUED. Evaluate the selected exoskeleton to assess how well it fits the worker, the level of assistance it provides, and the degree of mobility it allows.

Step 5 – Initial Ergonomics Risk Assessment

The fifth step entails conducting ergonomic risk assessments using the ACGIH HAL-TLV tool or any tool capable of monitoring ergonomic risk. The ACGIH TLV utilizes two independent variables: Hand Activity Level (HAL) and Normalized Peak Force (NPF) (Harris et al., 2021). HAL ratings range from 0 to 10, with 0 indicating "No regular exertion" and 10 indicating "Rapid steady Motion." The HAL scale, initially introduced by Latko et al. in 1997, incorporates work frequency and speed. In 2001, the ACGIH adopted the HAL-TLV ergonomic risk assessment tool, which combines HAL and NPF. The revised ACGIH HAL-TLV ergonomic risk assessment tool, introduced in 2018, ensures adequate protection against DUEDs for workers (Antonucci, 2019; Yung et al., 2019). This study utilized the revised ACGIH HAL-TLV. The HAL score presented in Table 1 was obtained using the regression equation in Eq. (1).

Table 1. Hand Activity Level Rating (adapted from Bernard and ACGIH (2002))

Verbal Anchor	Hands idle most of the time; no regular exertions	Consistent conspicuous long pauses; or very slow motions	Slow steady motion/exertions; frequent brief pauses	Steady motion/exertion; infrequent pauses	Rapid steady motion/exertions; no regular pauses	Rapid steady motion/difficulty keeping up or continuous exertion
Score	0	2	4	6	8	10

$$HAL = 6.5 \ln D \left[\frac{F^{1.31}}{1+3.18\,F^{1.31}}\right] \quad (1)$$

Where 'F' represents frequency, and 'D' represents the percentage duty cycle.

The NPF (Normalized Peak Force) required to perform a task represents the maximum force exerted by the hand during that task. It is normalized on a scale of 0 to 10, corresponding to 0 to 100% of the relevant reference strength (Drinkaus et al., 2005). The reference strength can be the strength of the worker performing the task, the strength of the industrial population, or another applicable reference (Harris et al., 2021). To determine the NPF for a task, it is essential to measure the hand forces and postures involved, obtain strength data for the specific worker or worker population in that posture, and calculate the NPF. The peak or required force is then divided by the appropriate strength or population reference, as shown in Eq. (2) (Drinkaus et al., 2005).

$$NPF = \frac{Peak\ force}{Strength} \times 10 \tag{2}$$

Table 2 presents the NPF rating and various methods for assessing hand force in a task, including qualitative and quantitative approaches. Qualitative methods involve the Moore-Garg Observer Scale, which requires ratings by a trained observer, and the subjective scale, which involves ratings by the worker. Quantitative methods utilize instruments such as electromyography sensors, grip meters, and force gauges (Seidel et al., 2021).

Table 2. Normalized peak force estimation for hand forces (adapted from Bernard and ACGIH (2002))

%MVC	Subjective Scale		Moore-Garg Observer Scale (Alternative Method)	NPF
	Score	Verbal Anchor		
0	0	Nothing at all		0
5	0.5	Extremely weak (Just Noticeable)	Barely Noticeable or Relaxed Effort	0.5
10	1	Very weak		1
20	2	Weak (Light)	Noticeable or Definite Effort	2
30	3	Moderate		3
40	4		Obvious Effort, But Unchanged Facial Expression	4
50	5	Strong (Heavy)		5
60	6		Substantial Effort with Changed Facial Expression	6
70	7	Very Strong		7
80	8			8
90	9		Uses Shoulder or Trunk for Force	9
100	10	Extremely Strong (Almost maximum)		10

After determining the HAL and NPF values for a task, these values are combined on the ACGIH HAL-TLV plot depicted in Fig. 2 to evaluate the overall risk level of the task. The plot consists of two lines: the Action Limit (AL) line and the TLV line. To plot the HAL and NPF values on the graph, a vertical line is drawn from the HAL value on the x-axis, and a horizontal line is drawn from the NPF value on the y-axis. The intersection of these lines with the TLV and AL lines determines the ACGIH HAL-TLV measure of the work-related risk associated with the task. The ACGIH HAL TLV measure utilizes the NPF and HAL scale to assess the task's risk level. If the NPF and HAL values fall below the AL line (green zone), the task is considered to have low risk and safe. If the NPF and HAL values fall between the AL and TLV lines (yellow zone), surveillance and action are required to prevent potential issues from becoming actual problems. If the NPF and HAL values surpass the TLV line (red zone), such as during a construction task with an exoskeleton, control measures can be implemented to reduce the risk to an acceptable level. This includes modifying the task to minimize hand activity and force exertion, as well as optimizing the exoskeleton to provide adequate support. Eqs. (3) and (4) display the equations for the Lines (ACGIH, 2018).

$$TLV: NPF = 5.6 - 0.56 \times HAL \tag{3}$$

$$Action\ Limit: NPF = 3.6 - 0.56 \times HAL \tag{4}$$

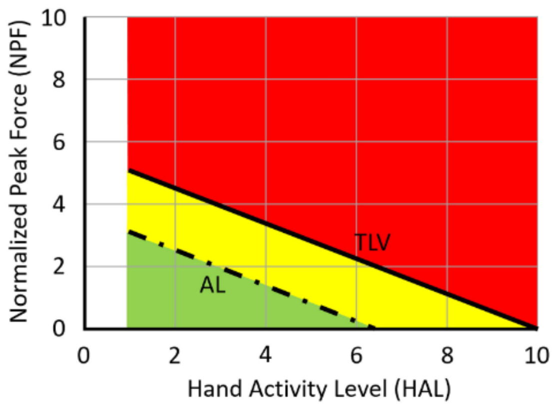

Fig. 2. ACGIH HAL-TLV plot (adapted from ACGIH 2018)

NB: Red zone (Threshold Limit Value) = high DUED risk, yellow zone = medium DUED risk, green zone (Action Limit) = low DUED risk

Seidel et al. (2021) developed a novel method for assessing the risk of HAL using objective measures exclusively, without relying on observation or video-based algorithms. They utilized kinematic and electromyographic sensor data to estimate the level of repetition and force involved in upper extremity movements, respectively. These measurements were then combined to calculate a measurement-based TLV for HAL, as demonstrated in Eqs. (5) and (6). The researchers tested their new method in the field and found a good correlation with observation-based methods (ρ = 0.847), indicating its potential as a promising tool for HAL risk assessment.

$$TLV: NPF_{measured} = 5.6 - 0.56 \times Repetition\ Score_{measured} \quad (5)$$

$$Action\ Limit: NPF_{measured} = 3.6 - 0.56 \times Repetition\ Score_{measured} \quad (6)$$

Step 6 – Develop/Adapt Interventions

After completing the risk assessment, the subsequent step involves developing or adapting interventions based on the assessment's outcomes. These interventions may include task redesign, adjustment of exoskeleton settings, or implementation of training programs to enhance worker techniques, particularly in situations where the risk is moderate or high. A primary goal of this step is to ensure that the proposed intervention is an ideal fit for the task, and that the intervention does not expose workers to adverse or unintended risks.

Step 7 – Evaluate Long-term Intervention Effectiveness

The final step is to periodically evaluate the effectiveness of the interventions in reducing the risk of DUED. This can be accomplished by establishing a system for ongoing monitoring and feedback, which enables the identification of potential issues and necessary adjustments, if necessary. Regular assessments help in detecting early signs of increased hand activity or force levels, allowing for timely intervention and modification. This step will help generate critical insight needed to verify the intervention's (exoskeleton) cost-effectiveness or return on investment.

These steps ensure that researchers and practitioners involved in exoskeleton assessment conduct a more comprehensive and rigorous evaluation.

3. Discussion

Previous studies have demonstrated that exoskeletons can reduce muscle activation (Antwi-Afari et al., 2021; Bock et al., 2012; Gonsalves et al., 2021). However, limited information is available regarding the actual risk reduction provided by exoskeletons in preventing hand-related disorders. Additionally, certain exoskeleton designs may restrict hand movement, potentially increasing the risk of DUED (Tran et al., 2021). This study aims to evaluate the DUED risk levels faced by workers utilizing exoskeletons in construction tasks.

The conceptual framework utilizes the ACGIH HAL-TLV tool to assess HAL and NPF ratings during the tasks. By plotting these ratings on the ACGIH HAL-TLV graph, the worker's position is determined (below AL, between AL and TLV, or above TLV). Ratings below the AL indicate that the worker is safe with the exoskeleton. Ratings between AL and TLV require surveillance to prevent potential issues. However, if the rating exceeds the TLV, it indicates a high DUED risk, necessitating immediate action to enhance worker safety. Siedel et al. (2021) have demonstrated that the ACGIH HAL-TLV can be automated using various sensors, such as kinematic, kinetic, and electromyographic sensors. This means that manufacturers of exoskeletons used in construction tasks can incorporate these sensors to capture variables such as hand posture, repetition, and force exertion. With this data, the exoskeleton can estimate the worker's risk level and adjust itself to provide the necessary support, reducing the worker's risk level to an acceptable range.

By incorporating the ACGIH HAL-TLV in exoskeletons designed for construction tasks, the exoskeletons can be tailored to meet HAL-TLVs for different levels of hand activity, thereby reducing the risk of injury for workers. This approach ensures worker safety, leading to improved performance, productivity, and reduced risk of DUED. Therefore, incorporating a process for measuring DUED risk in exoskeleton design or in its assessment when used to execute construction tasks is a crucial step in safeguarding worker safety and health.

In the absence of an automated process for DUED risk assessment, researchers and practitioners assessing the impact of exoskeletons can utilize the manual process within the ACGIH HAL-TLV to evaluate worker risk exposures. This assessment, combined with muscle activation and other biomechanical evaluations, provides a comprehensive understanding of the true impact of exoskeletons.

4. Conclusion

The high physical demands of construction work, including material handling, repetitive hand motions, and force exertion, pose an increased risk of Distal Upper Extremity Disorders (DUED), making it a significant occupational health concern in the construction industry. The impact of exoskeletons on DUED in the construction industry remains unclear. This study has developed a comprehensive conceptual framework for evaluating and controlling workers' exposure to DUED when performing construction tasks using ergonomic interventions. The framework adopts a nuanced and targeted approach to exoskeleton assessment by considering specific risks associated with different tasks and worker populations. It incorporates the American Conference of Governmental Industrial Hygienists (ACGIH) Hand Activity Level - Threshold Limit Value (HAL – TLV) risk assessment tool into the assessment process. By following the steps outlined in this framework, including job risk assessment, identifying the target population, defining tasks, determining exoskeleton design, conducting ergonomic risk assessments, developing interventions, and evaluating their effectiveness, safety researchers and practitioners can reduce the risk of hand-related injuries among construction workers. While acknowledging the potential benefits of exoskeleton use, this framework recognizes the need for a holistic and nuanced approach to evaluate and address potential risks associated with exoskeleton use in the context of construction work. The framework will be valuable to practitioners in the construction industry responsible for implementing safety programs and policies. One limitation of this study is its focus on exoskeletons specifically designed for hand-related construction tasks. Future research should explore assessing the efficacy of exoskeletons in reducing the occurrence of Work Musculoskeletal Disorders (WMSDs) when providing support to other body parts, including the shoulder, back, and lower limbs, during different construction tasks. Additionally, this study did not test the developed conceptual framework. Subsequent studies should incorporate testing of the conceptual framework and provide recommendations for its improvement if necessary.

Author Contributions

Abdullahi Ibrahim contributes to conceptualization, methodology, draft preparation, manuscript writing, editing, and visualization. Chukwuma Nnaji contributes to conceptualization, methodology, validation, draft preparation, manuscript editing, visualization, supervision, project administration. Xi Wang contributes to manuscript writing and editing. All authors have read and agreed with the manuscript before its submission and publication.

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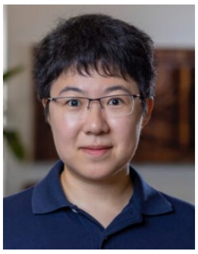

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