HAZARD CONTROL

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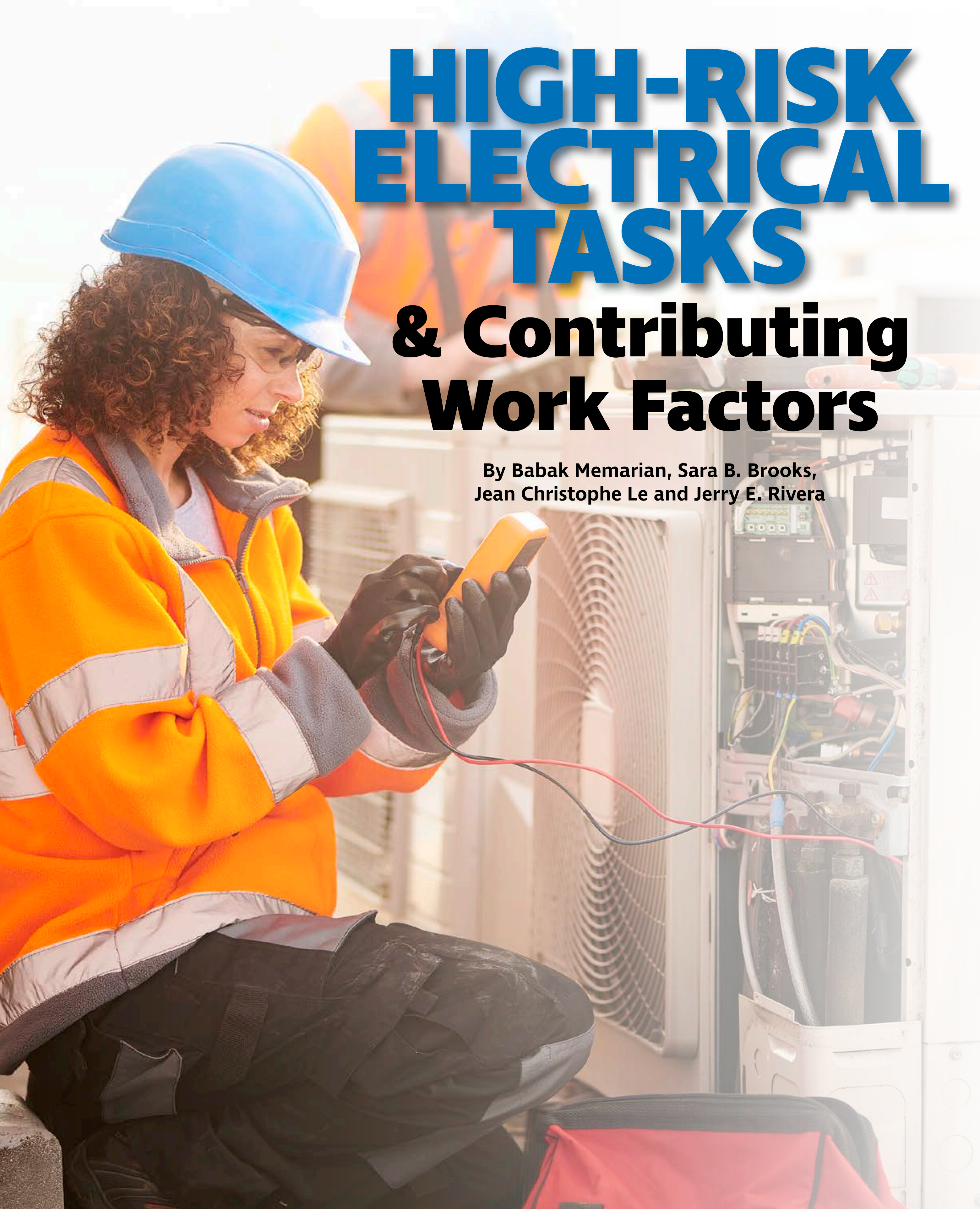

HIGH-RISK ELECTRICAL TASKS & Contributing Work Factors

By Babak Memarian, Sara B. Brooks, Jean Christophe Le and Jerry E. Rivera

ELECTRICAL CONSTRUCTION is identified as a high-risk trade, and electricians accounted for about 8% of all fatalities in the construction industry in 2019 (BLS, 2021). Electrical operations are typically highly technical and complex, and electricians can be exposed to various hazards that can lead to injuries and fatalities. Electrocution is known as one of the leading causes of fatalities in electrical construction as well as other trades (OSHA, 2011). Other analyses report contact with overhead power lines, faulty wiring, contact with energized equipment, improper PPE and faulty construction tools as the leading causes of occupational injuries involving electric shock (Casini, 1993; Doan, 2019; Hinze et al., 1998).

Although electricians are at a higher risk of injury and fatality due to electrical incidents compared to other trades, the impact of these incidents is wide-ranging. Other work groups including laborers, structural metalworkers, painters, roofers and linemen also experience an increased risk of injury and fatality due to contact with electricity (Casini, 1993; Ore & Casini, 1996; Suruda, 1988).

Despite the importance, limited research has been conducted to delve deeper into the mechanism of incidents and explore underlying factors contributing to the increased burden of electrical injuries and fatalities in construction. Studies that have attempted to fill this gap have some limitations. A 2009 study examined workers' compensation claims to identify the causal factors of nonfatal injuries involving contact with electricity (Lombardi et al., 2009). A similar investigation was performed in 2013 based on BLS data. However, these studies included all industry sectors, limiting their applicability to construction (Cawley & Brenner, 2013).

A more recent study utilized OSHA's Integrated Management Information System data to analyze trends in occupational incidents in electrical construction (Gholizadeh et al., 2021). This study provided important quantitative insights and identified malfunctions in lockout/tagout (LOTO) procedures, inappropriate position, and the removal or inappropriate use of safety devices as the main precipitating factors in electrical fatalities. However, it was based on data gathered through legally mandated incident and injury reporting, which contains insufficient supplemental data on tools and equipment, mitigating circumstances and unique challenges (Hinze et al., 1998). Moreover, they do not capture near-misses, a valuable source of data for incident prevention (Williamsen, 2013).

KEY TAKEAWAYS

- **This study takes a deeper look at electrical tasks, going beyond statistics, to explore task-specific information from practitioners' perspectives to enhance the quality of pretask planning during the process of electrical operations.**
- **This project identifies high-risk electrical tasks and explores work factors constituting at-risk working conditions for each activity. It then introduces innovative controls to recognize and mitigate hazards.**
- **The findings of this study emphasize the importance of proper lockout/tagout as the centerpiece of risk control practices in electrical work. It further discusses the application of advanced technologies to enhance the quality of hazard recognition.**

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Pretask Planning & Preventive Practices

In electrical construction, the most serious incidents often involve the uncontrolled release of hazardous energy. For this reason, de-energization is the primary control method employed to prevent catastrophic injuries. Outages that are properly planned, implemented and verified can completely remove hazardous energy from electrical systems so that work can be safely performed. However, these outages are often infeasible in public locations that require continuous power such as hospitals or utilities. LOTO is an alternative control that is frequently employed to de-energize systems in part or in full and restrict unauthorized re-energization. It can be highly effective when implemented correctly (OSHA, 2011). Improved training, for both management and craft, has proven to increase the success of LOTO programs as well as electrical safety programs in general (Gammon et al., 2019; Neitzel, 2018).

Lean construction is defined as an organizational approach initially intended to reduce waste, maintain workflow, decrease cost, increase productivity and enhance project quality. However, research findings suggest that application of lean construction principles and tools can also enhance project safety (Gambatese et al., 2016). In the context of electrical construction, the application of lean principles can include the proper use of labels and tags, which provide workers with visual cues and detailed information on voltage and energization status of electrical equipment. This practice can reduce the risk of exposure to hazardous energy and consequent injuries and fatalities. Moreover, systematic storage of materials and tools, and removal of unneeded items can reduce exposure to trip hazards and enhance efficiency by reducing search time (Fardhosseini et al., 2021).

Research Objectives

Research findings suggest that most occupational incidents are preventable if hazards are recognized properly and addressed proactively (Memarian et al., 2022; OSHA, 2012). Understanding the task factors and project attributes contributing to incidents and injuries can paint a more complete picture of the interventions needed to prevent future incidents. This emphasizes the importance of implementing effective pretask planning and job hazard analysis (JHA) to reduce occupational incidents and injuries. A well-established pretask plan augmented by task-specific information can help identify potential hazards, develop mitigation strategies and recommend necessary controls (Madhuwanthi et al., 2019). However, the current body of knowledge in electrical construction safety lacks this comprehensive information all in one place. To fill this gap and help enhance the quality of JHA and pretask planning in electrical construction, this study pursued three objectives: 1. identify high-risk and highly complex electrical tasks and operations; 2. explore task factors and project attributes contributing to incidents and near-misses from practitioners' perspectives; and 3. identify applied interventions and solutions for each task to help enhance electrical workers' safety and health.

Methodology

To deliver the project objectives, four major activities were performed in the following order: 1. convene an

TABLE 1

HIGH-RISK ELECTRICAL TASKS & CONTRIBUTING FACTORS

Tasks	Contributing factors
Demolition or removal of electrical equipment	• Improper control of energy from live equipment • Unsecured components • Poorly installed equipment with missing drawings or labels • Inadequate and inconsistent training • Exposure to unknown particulate
Site work, layout and logistics	• Congested jobsite • Uneven terrain or ice • Improper lift techniques • Improper mobilization equipment
Prepare ground for underground electrical installations	• Striking unground live lines or energized feeders • Trench preparation and excavation • Hazardous atmospheres (e.g., manholes and duct banks) • Tight workspace • Procedure violation: using stronger chipping guns to accelerate progress • Poor-quality inspection due to dirt obscuring wire coatings
Pull cables and wires	• Improper ergonomic techniques and awkward posture due to tight workspaces • Not using mechanical aids to move reels • Improper use of the tugger • Sharp edges (e.g., HVAC ductwork) • Long-distance pull operations
Lockout/tagout (LOTO)	• Not following LOTO policies and procedures • Not reviewing electrical one-line diagrams and documents • Not having correct LOTO device • Unexpected release of stored energy from test equipment and back feeds • Performing LOTO on complex systems: LOTO-specific breakers while keeping other breakers in operation
Operate trucks with boom lifts or standalone lifts	• Contact with overhead lines or objects from hauling high-profile equipment • Not having a spotter in place • Lack of overhead hazard recognition
Produce openings for conduit and electrical lines	• Working near live equipment • Striking a live line within a wall or floor • Struck-by objects from overhead drilling • Wrong choices of drill bit and hole saw for the core drill • Working around public
Installation of new electrical equipment	• Complex configuration of electrical equipment • Tight workspace • Improper coordination of overhead or stacked work • Uncomfortable PPE and awkward posture in tight workspace • Failure to inspect and improper use of equipment and tools • Untethered tools and materials • Inadequate insulation • Improper control of energy
Preventive maintenance on electrical equipment	• Complex LOTO procedure due to multiple switchgear and unaccounted feeds • Failure to follow LOTO procedures • Contact with energized parts (e.g., conductors and bus bars) • Overloading load bank • Faulty load banks and cables • Improper connection to load bank
Energize electrical equipment	• Incomplete, incorrect or mislabeled installations • Failure to follow the LOTO procedures • Using conductive tools • Improper control of downstream devices • Circuit breaker failure causing arc flashes and igniting combustible dust

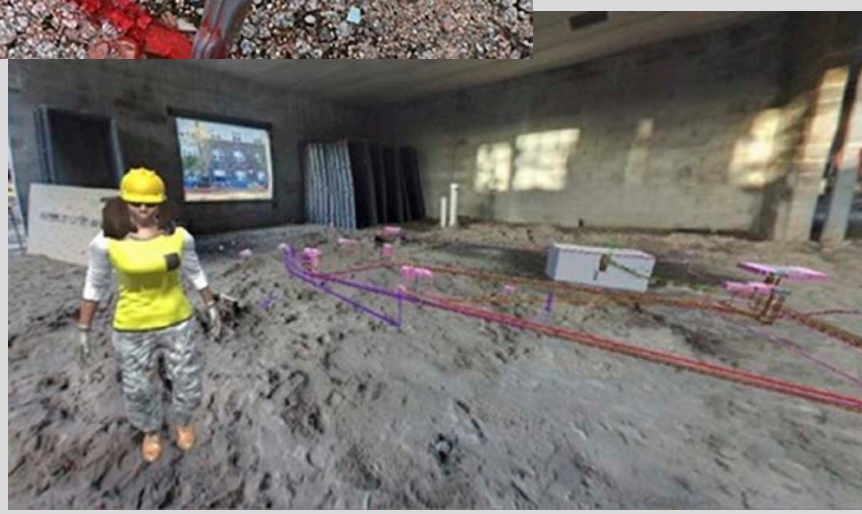

Photo 1 (above): A cable locating device. These devices use geospatial technology and rely on electromagnetic sensors or radio frequency and ground-penetrating radar to map components below the surface.

Photo 2 (right): An AR training module for underground electrical systems can be used to enhance workers' hazard recognition skills.

industry advisory group; 2. develop the data collection instrument; 3. recruit participants; and 4. collect data.

Convene an Industry Advisory Group

To enhance the quality and reliability of findings, the first step was to convene an industry advisory group. This group comprised 10 subject matter experts in construction safety and health representing electrical construction contractors, unions and trade associations. The advisory group's role was to review the design of the data collection instrument and examine research findings through an iterative process. The advisory group also facilitated recruiting the research participants.

Develop the Data Collection Instrument

An inquiry form was developed to identify high-risk electrical tasks and detailed information on associated work factors that create hazardous working conditions from practitioners' perspectives. The form was revised and finalized based on the industry advisory group's comments. The form included instructions for participants and provided a blank table to capture their responses. No answer choices or prepopulated lists were provided. Respondents were first asked to list high-risk electrical tasks based on their own experience in the first column and provide supplementary information on contributing factors in the corresponding spaces for each operation including: 1. potential incidents or near-misses; 2. associated tasks or subtasks; 3. tools or equipment; 4. materials; and 5. unique challenges. The final version was reviewed and approved by the CPWR—The Center for Construction Research and Training's institutional review board.

Recruit Participants

In collaboration with the industry advisory group, the data collection form was sent to 18 company representatives from electrical and general contractors. Companies were selected using a convenience sampling approach.

Collect Data

Participants were given 3 weeks to complete and return the form to the research team. Fourteen company representatives completed and returned the form, yielding a 78% response rate.

Findings

Each of the 14 completed forms received contained between two and 11 discrete electrical tasks that respondents identified as high risk. These tasks were accompanied by work factors that respondents believed contributed to the elevated level of risk. After cleaning and processing the data, 10 major tasks were identified. Each major task was populated with the contributing factors provided by respondents (Table 1).

Discussion & Conclusion

To develop a comprehensive pretask plan and implement effective controls, access to detailed task-specific information is essential. Since electrical hazards can impact other trades on the jobsite, access to this information is vital for all trades working on or near electrical equipment and installations. To fill this gap in the current body of knowledge, in close collaboration with construction practitioners, this study first identified high-risk electrical tasks. It then explored work factors associated with each operation that create hazardous working conditions and contribute to incidents and near-misses from practitioners' perspectives. Finally, it sought to identify applied, task-specific interventions to enhance safety and health in electrical construction. The findings of this study are discussed further in the following sections.

To create a safer, healthier workplace for construction workers, it is crucial to proactively identify hazards and provide proper controls to mitigate them.

Energized Equipment & LOTO

Failure to adequately control electrical energy sources was identified as a major risk factor during multiple operations, which was mainly attributed to performing improper LOTO. This can be a result of a lack of proper LOTO devices, not following the LOTO procedure, and performing LOTO on complex electrical systems. Furthermore, from a human factors perspective, involvement of multiple trades in the LOTO process can increase the likelihood of error. Application of effective administrative controls including updating LOTO procedures and policies, conducting periodic LOTO training, and improving the quality of communication and coordination among trades are strongly recommended. Having qualified electrical personnel responsible for LOTO has also been proven to significantly reduce procedural mishaps (NFPA, 2021). Employing advanced engineering controls where feasible can reduce the LOTO failure rate.

Labels and tags on electrical components including incident energy analyses and manufacturer labels communicate information that is essential for safe installation and maintenance of electrical systems. They document system voltage or fault current, or warn of an arc-flash hazard, among other purposes. As the findings of this study also revealed, missing or incorrect labels increase the risk of contact with uncontrolled energy. OSHA's (2008) general industry standard requires adherence to all labeling instructions, however, there is no equivalent requirement in construction. Although OSHA may use other mechanisms such as the General Duty Clause to issue citations, its reach as an agency can be limited depending on location, with approximately one compliance officer per 70,000 workers (OSHA, n.d.).

Defective and improperly maintained electrical equipment, tools, and devices can produce hazardous conditions for both workers and future occupants. Respondents identified faulty circuit breakers, broken cables, faulty load banks and defective LOTO devices as a few examples. Therefore, it is essential to conduct periodic and thorough assessments of the quality and working conditions of electrical equipment and controls as outlined by pertinent codes and standards. There are also emerging technologies that, if adopted early in the design or redesign stage, can significantly reduce worker exposure to hazardous sources of energy. For example, permanent electrical safety devices eliminate worker exposure to energized electrical circuits when verifying the absence of voltage via means of guarding.

Accidental Contact With Power Lines

Accidental contact with underground cables was identified as a major risk in electrical operations. Excavation-related incidents account for nearly one-third of all incidents related to utilities (Talmaki et al., 2010). Unlike other types of infrastructure, underground cables are difficult to accurately locate. Dirty and debris-covered structures were identified as factors that increase the complexity of this task. This can lead to accidental contact with power cables during excavation, when using a jackhammer or when trenching for underground installations, which can result in electrocution, shock or burns. Therefore, it is vital to employ proper interventions that can help minimize the risk of worker exposure to the hazards involved in ground-penetration work. Workers may employ handheld cable-locating devices that use geospatial technology and rely on electromagnetic sensors or radio frequency and ground-penetrating radar to map components below the surface (Photo 1, p. 17). Where feasible, application of advanced technologies such as geospatial augmented reality (AR) to visualize and monitor underground utilities and their proximity to equipment is recommended. These software applications translate geographic data from the U.S. Geological Survey into 3D markers that indicate underground power line locations in real time.

A lack of overhead hazard recognition was identified as a major factor causing accidental contact with overhead lines while operating high-profile equipment including dump trucks and boom lifts. As noted, the application of advanced technologies has played a critical role in enhancing the accuracy of live line detection. Proximity warning devices can immobilize heavy equipment when it reaches a certain height (Koustellis et al., 2011). These warning devices use an electric field sensor to alert the operator if mobile equipment moves within a minimum distance of an energized overhead power line. These devices can be mounted on heavy equipment or on the load itself. This can reduce safety risks that might occur if the operator or spotter is distracted and the equipment is tracking into live lines (CPWR, 2016). However, there is still no replacement for competent spotters to prevent accidental contacts with power lines, especially overhead lines.

Some of these incidents are attributed to distractions, fatigue and cognitive overload, especially those involving operators and spotters. When overall workload exceeds capability, hazard recognition can suffer, and the likelihood of incidents increases (Memarian & Mitropoulos, 2016). Some techniques that have been successfully used to remedy cognitive overload include frequent rest breaks, limited overtime, stop work authority, and matching task complexity with capability and experience (Mitropoulos & Memarian, 2013).

Training Requirements

Improper work practices and inadequate use of equipment were cited as major challenges producing hazardous conditions in electrical operations. These can collectively stem from insufficient or lack of proper electrical safety training (Gammon et al., 2019). In addition to traditional classroom and on-site training modules, electrical construction can benefit from technologies including virtual reality and AR (Photo 2, p. 17) to enhance workers' hazard recognition skills (Wen & Gheisari, 2021).

Spatial & Ergonomics Considerations

Tight workspaces and complex electrical equipment configurations are two major work factors identified by respondents that increase electrical workers' task difficulty and exposure to hazards. These conditions make it difficult to maneuver, properly lift items and perform tasks that can increase the risk of contact with sharp objects. Performing tasks in tight workspaces sometimes requires workers to take an awkward posture and does not allow for the operation of mechanical lift devices. This increases the need for manual material handling that can result in a higher risk of work-related musculoskeletal disorders. In such conditions, application of exoskeleton assistive devices and proper PPE is recommended to protect workers (Dale et al., 2016; van Engelhoven et al., 2018). Moreover, application of building information modeling (BIM) is recommended to improve work coordination among trades (Wetzel & Thabet, 2015). BIM is a concept that integrates multidisciplinary data to generate a digital representation of a construction project throughout its life cycle. Through virtual mapping of the building layout and project schedule, it can facilitate sequencing activities in logical order to avoid potential clashes (Azhar, 2011; Rajendran & Clarke, 2011). For example, contractors using BIM could identify an electrical task to be performed prior to the installation of bulky equipment that would block access to relevant electrical components.

Project information in BIM can be analyzed in the early project planning stages to reduce safety risks as well (Akram et al., 2019; Kim et al., 2016). BIM enables automatic scanning and detection of hazardous conditions in construction projects. Supplemental programs that integrate predefined rule sets such as design safety codes and OSHA regulations can be installed to work in conjunction with BIM (Hongling et al., 2016). This allows the capability to analyze dimensional variables and create color-coded visual overlays on a model to characterize the level of potential risk for each defined hazard.

Exposure to Unknown Particulates

Electrical work involves a significant amount of cutting, drilling and other tasks that increase the risk of exposure to airborne particulate. On older jobsites, these particulates may be of unknown composition. In addition to acute safety hazards, these operations have the potential to pose serious health hazards over the long term. Employing predictive tools to assess exposure to these hazards and proactively addressing them is vital to maintaining a healthy workforce. One such tool, the Exposure Control Database (**https://bit.ly/3PNDMyK**), estimates exposure to silica, welding fumes, lead or noise based on the task and working conditions. This information can be used to proactively select the most effective engineering controls and PPE, especially if air sampling is not feasible (Memarian et al., 2020).

Limitations & Future Research

To create a safer, healthier workplace for construction workers, it is crucial to proactively identify hazards and provide proper controls to mitigate them. This fact highlights the importance of effective pretask planning in construction projects. To help enhance the quality of pretask planning, the study presented in this article investigated high-risk electrical tasks and identified contributing task factors and project attributes from practitioners' perspectives. It then explored and introduced applied solutions for each operation, including the application of advanced technology in hazard recognition.

However, the findings of this study were limited to responses from 14 electrical construction contractors, which may not be considered a representation of the whole construction industry. Moreover, responses may be limited to respondents' personal experiences, so the findings should not be generalized across the construction industry. Thus, further research is needed to examine the findings of this study on a larger scale.

This study built a foundation for further task-specific research in electrical construction and other trades. From a practical perspective, a logical next step would be the development of an information management system containing task-specific information and evidence-based controls to mitigate hazards. Electrical contractors, especially smaller ones with limited resources, can benefit from such a system to enhance the quality of pretask planning. **PSJ**

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