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# Adoption of Wearable Exoskeletons for Worker Safety in the U.S. Construction Industry: A Scoping Review of Drivers and Barriers

Tolulope Oyeyipo[1], Ibukun Awolusi[1], and Tulio Sulbaran[1]
[1]The University of Texas at San Antonio

While the construction industry has embraced the adoption of wearable technology, the level of adoption of wearable exoskeletons in the US construction industry is limited and in the infancy stage. The user acceptance and implementation of wearable technology have been influenced by several factors among others. A sizable number of studies have been carried out on the adoption of wearable exoskeletons in the US construction industry but there is a need to identify the impacting factors on the technology implementation. Considering the new area of the application of exoskeletons in the construction industry, a scoping review is conducted to identify the drivers and barriers to the implementation and use of exoskeletons in the US construction industry. The findings of the study showed that drivers such as reduction of fatigue, safety and health awareness, and future standard equipment have the potential to improve exoskeleton adoption in the US construction industry while cost constraints, discomfort, privacy issues, and resistance to change are significant barriers identified. The review provides checklists of actionable steps towards increased adoption of exoskeletons and guidelines for policymakers, contractors, and safety managers on the drivers and barriers in order to make informed decisions on exoskeleton adoption in the US construction industry.

Keywords: Construction, Musculoskeletal Disorders, Wearable exoskeleton, Worker Safety, US

## Introduction

Although the construction industry is known to contribute to economic development in the US, the industry has the highest number of non-fatalities and illnesses relating to work-related musculoskeletal disorders (WMSDs) (Gonsalves et al. 2024). Construction tasks are performed at a fast pace in a dynamic and complex work environment with task variability including bending, lifting, carrying, over-the-shoulder works, and non-neutral or prolonged static postures (Gutierrez et al., 2024, Kim et al. 2023) causing construction workers to experience high rates of WMSDs. The impacts of WSMDs are quite extensive, affecting the construction workers at both personal and social levels. According to Govaerts et al. (2021), this invariably increases workers' absenteeism, reduces productivity, and impairs their health and quality of life; causing significant financial loss and high treatment costs to construction companies. In the wake of the high fatalities and risk factors associated with WMSDs in the US construction industry, there has been increasing attention given to the adoption of wearable technologies such as exoskeleton that supports workers' health, safety, and ergonomics.

Gonsalves et al. (2023) defined exoskeletons as a wearable assistive device external to the body that actively or passively supports joints. The supports are expected to stabilize or facilitate body movement, promoting the well-being of the workers in the process (ASTM, 2019, Anti-Afari et al, 2021). The technology is particularly essential for workers engaged in repetitive work where WMSD risk factors such as awkward positions, twisting, kneeling and other related activities are part of construction activities or tasks. Exoskeletons also known as wearable robots worn externally to support human movement and enhance the power of a person to reduce physical strain and injuries on construction sites.

Exoskeletons have been used in several industries such as manufacturing, healthcare, and automobile among others. While the construction industry has embraced the adoption of wearable technology, the level of adoption of wearable exoskeletons in the US construction industry is limited and at the infancy stage (Mahmud et al., 2022, Gonsalves et al., 2023). Although the use of exoskeletons has numerous benefits and drivers for adoption in the construction industry, studies have shown that high initial cost, limited awareness, lack of evidence detailing its benefits, and perceived weight are a few of the significant inhibiting factors (Gonsalves et al., 2024; Kim et al., 2019). Although a sizable number of studies have been carried out on the adoption of wearable exoskeletons in the US construction industry, there is a need for a scoping review of the impacting factors on the technology implementation. Therefore, this study provides a review of drivers and barriers to the adoption of wearable exoskeletons in the industry. This study is significant due to the presence of little to no comprehensive studies about exoskeleton adoption barriers and drivers in the construction industry. The scoping review will provide the foundation for future studies geared toward enhancing the implementation and use of the technology in the US construction industry. The specific focus on US construction will reveal considerable region-specific information that will be essential for setting standards and regulations for the improved use of the technology.

## Research Methodology

The study adopted a scoping review to achieve the objectives of the study. A scoping review allows the mapping and summarizing of existing studies on the factors influencing the adoption of exoskeletons in the US construction industry. Arksey and O'Mallery (2005) revealed that a scoping review presents the breadth and depth of existing literature, identifying research gaps in the literature and clarifying key concepts relating to the subject matter. The study of Munn et al. (2018) reiterated that a scoping review is an ideal tool that provides available evidence, analyses research gaps, and elucidates key concepts and methodologies used in a particular research focus. The scoping review is appropriate for the study because exoskeleton adoption research is limited, diverse, and fragmented. The methodology will provide an overview of the factors influencing the adoption of exoskeletons with the aim of developing an aggregated highlight of both the promoting and inhibiting factors that guide the adoption process.

### *Data Sourcing and Collection*

Document search for the scoping review was limited to publications domiciled in the Web of Science (WoS) database. Other sources like Google Scholar and Scopus, were not used to reduce duplication. Using multiple databases results in significant overlaps in retrieved articles, ensuring that considerable effort is needed for screening for the study The choice for the use of WoS is based on the comprehensive coverage of high-impact journals, reliable peer-reviewed sources, and advanced search and filtering capabilities (Meho & Yang, 2007, Pranckutė, 2021). More so, recent studies have acknowledged WoS as one of the common databases with high-quality journals (Chavarro et al., 2018). The use of WoS in carrying out varying forms of review has been used by several researchers in the construction management domain. However, at the time of carrying out this study, there has not been any review on exoskeleton adoption in the construction industry. Figure 1 depicts the research methodology adopted for the study. The publications were found relying on the following group word combination for WoS query: "wearable exoskeleton" OR "wearable technology" OR "exoskeleton" AND "construction industry" OR "US construction" OR "construction" AND "safety" OR "worker safety" OR "MSD" OR "musculoskeletal disorders".

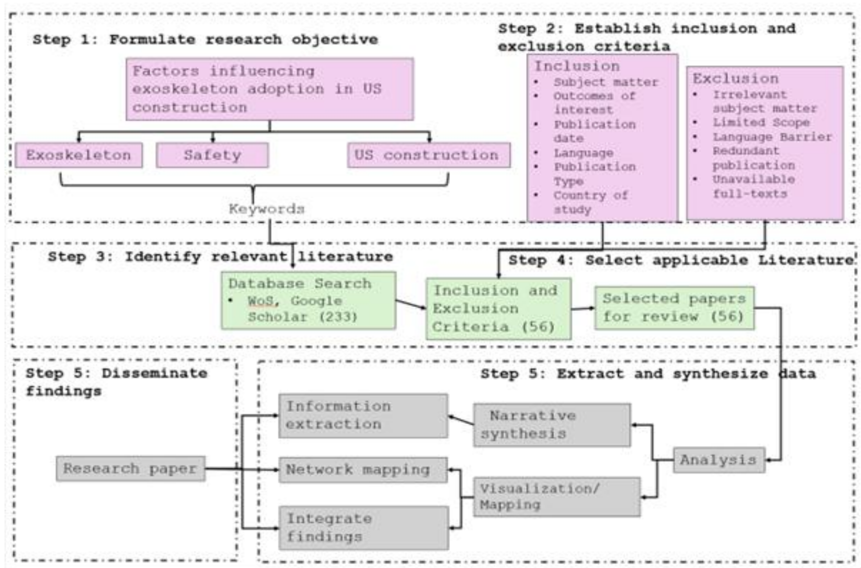


**Figure 1.** Research Methodology

*Search Strategy and Data Purging*

About 233 publications (articles, conference proceedings, reviews, short surveys, and editorials) were retrieved from the database. In order to achieve a much better output, only peer-reviewed articles and conference proceedings were identified for purging for further analysis. The choice of both forms of publications offers more precise and valuable evidence due to the laborious process in the construction journal field (Makabate et al. 2022). To ensure that a wide range of reviews is covered for this research, other forms of search criteria were used in the search engine documents for the English language and delimited to US construction. Because of the evolution of wearable exoskeletons, articles were limited to the last ten years (i.e. between 2014-2024). Following this result, a more critical and visual search was done, and another query was set to target only publications carried out within the US construction industry to help improve the study's relevance and eligibility which resulted in 56 articles as seen in Figure 1. The Inclusion and exclusion criteria can be found in Table 1.

**Table 1.** Article Inclusion and Exclusion Criteria

| **Inclusion criteria** | **Exclusion criteria** |
| --- | --- |
| • Articles relating to exoskeleton adoption in the US construction industry were used for the analysis<br>• Publications written in English Language only<br>• Articles domiciled in the WoS database are used for the review<br>• Publications were limited to the last ten years | • Articles related to exoskeleton adoption and use outside of the construction management domain<br>• Non-peer-reviewed and/or peer-reviewed publications such as editorials, conference proceedings, book chapters, website pages, video |

*Bibliometric Technique and Content Analysis*

The study adopted a bibliometric technique to quantitatively map out bibliometric data in a particular network and pattern as evident in the studies of Makabate et al. (2022). The benefit of this approach is the ability to scientifically map out relevant information for works of literature. Several tools have been developed and used for science mapping like Cite Space, Gephi, R, VOSviewer, etc. These tools all have disparate strengths, capacities, and limitations but are generally developed for science mapping. Olawumi and Chan (2018) argued that VOSviewer, an open-source data analytical tool is a text-mining tool used by researchers in construction management studies. In addition, the data extraction and analytical tools used for scoping review are content analysis with Excel. The tracking, summarization, and classification of the relevant themes were carried out using Excel.

## Results and Discussion

*Network Mapping of Co-occurring Keywords*

The network mapping of co-occurring words presented in Table 2 underscores the interconnection of four clusters namely, health and MSDs, technology adoption and management, systems and exoskeleton, construction safety, and performance. The network underpins the interrelationships between the clusters and the role each plays in the adoption of exosuits in the construction industry. The clusters and their associated relevance to the scoping review on exoskeleton adoption in construction are presented below.

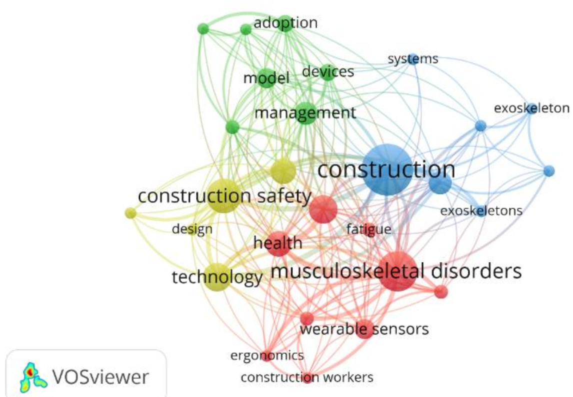


**Figure 2.** Co-occurring keywords

*Health and Musculoskeletal Disorders (MSDs)*

The red cluster underscores the health-related benefits such as the reduction of MSDs and fatigue associated with the implementation of exoskeleton in the delivery of construction projects. The ergonomics issues responsible for causing the disorders are as a result of repetitive work, heavy lifting, and awkward postures workers are exposed to on construction sites. The health benefits of reducing MSDs and fatigue in the workplace are key motivating factors for the implementation and use of wearable exoskeletons in the US construction industry (Nnaji et al. 2021, Awolusi et al. 2023, Gonsalves et al. 2023, Dobrucali et al. 2024). The design of the technology prevents injuries of construction workers and most notably improves their overall health in the long run. These benefits are particularly essential as they connote fewer accidents, higher productivity, and reduced cost implications for treating fatalities.

*Technology Adoption and Management*

The green cluster denotes the technology adoption relating to the exoskeleton and the importance of user acceptance and organizational management supporting the adoption. As it is with many new technologies, there is usually resistance to change that affects general acceptability by proposed users of the technology (in this case, workers). However, studies showed that top management support (Huang et al. 2021) and practical demonstration (Mahmud et al. 2022, Gonsalves et al. 2024) are important drivers for improving the ease of using the technology (Okpala et al. 2022, Okunola et al. 2024) in construction processes. The top management within organizations will reinforce the benefits of increased acceptance by making concerted efforts for practical training and demonstrations.

*Construction Safety and Performance*

The yellow cluster is regarded as 'construction safety and performance' theme. The theme focuses on improvement in construction safety performance which is the result of using exosuits. There is a positive correlation between exoskeleton adoption and improved ergonomics which will reduce fatalities on construction sites. The reduction of fatigue and increased endurance are significant motivators for the adoption of exoskeletons (Hondzinski et al. 2018, Guttierez et al. 2024) and become crucial in reducing compensation costs associated with fatalities (Okunola et al. 2024). There is a possibility of improved work performance with reduced loss of time and increased productivity of workers.

*Systems and Exoskeletons*

The final cluster termed systems and exoskeleton are shown in blue as depicted in Figure 2. Exoskeleton sets out to provide solutions to the existing workplace systems and problems to which workers are exposed. The technology is particularly useful for a reduction in muscle activity during construction tasks and activities (Kim et al. 2018) and soon will become a regular standard equipment in the coming years as predicted by a few recent studies (Guttierez et al. 2024, Gonsalves et al. 2024, Kim et al. 2024). This theme supports the notion that exosuits will become standard equipment to be worn by construction workers before embarking on their work on site. It is imperative that each theme listed presents the notion that promoting factors will increase exoskeleton implementation in the US construction industry.

*Factors Influencing the Adoption of Exoskeletons in the US Construction Industry*

The review of the literature provides a comprehensive checklist of the factors that positively and negatively affect exoskeleton adoption in the US construction industry. This section is hitherto divided into drivers and barrier factors affecting the exoskeleton adoption in the construction industry.

*Drivers of exoskeleton adoption in US construction*

The review identified more than 58 driving factors influencing positively the adoption of exoskeletons in the US construction industry. After reviewing for duplication and repetitions, the factors were pruned down to 16 drivers for exoskeleton implementation in the construction industry as shown in Table 2. One of the significant driving factors for exoskeleton adoption as evident in nine articles is the reduction of fatigue of workers (Nnaji et al. 2023, Gonsalves et al. 2024) during active work hours on site. In other related studies, it was established that wearing technology relieves related pain experienced from repetitive work and awkward postures on construction sites (Guttierez et al. 2024). Other important driving factors as highlighted in Kim et al. (2024) include but are not limited to ease of use, safety and health awareness, future standard equipment, compatibility with specific trades, and prevention of WMSDs among others. Following the increased attention given to exoskeleton usage in US construction, over time the technology will become a regular safety equipment. Similarly, the potential of exoskeletons to reduce body strains and invariably prevent musculoskeletal disorders makes it imperative for construction companies to adopt the technology for construction safety. Another motivation lies in the ability to have real-life scenarios in a virtual setting allowing for first-hand demonstrations and training for effective workers' use. This feedback is particularly critical for continuous learning and improvement. Similarly, Kim et al. (2018) and Zheng et al. (2024) confirmed that the exoskeleton supports muscle activity and provides varying passive ergonomics benefits. Enhanced productivity is another factor that positions the technology for improved acceptability and implementation in US construction (Mahmud et al. 2022, Kim et al. 2018). For construction workers, exoskeletons ensure that there is no pain and hence perform their tasks more efficiently. Employers have less loss of time and slippages arising from body pain and other ergonomics for better safety performance and project performance outcomes.

**Table 2.** Drivers of the Adoption of Exoskeletons in the US Construction Industry

| **Drivers** | **Description** | **Sources** |
|---|---|---|
| Adaptability to environmental challenges/stressors | Ability to perform reliably and safely under varying weather conditions | Kim et al., 2018; Okunola et al., 2024; Pillsbury et al., 2019 |
| Cost-effectiveness and benefits | A balance between initial investment and long-term savings on injury rates | Awolusi et al., 2023; Gonslaves et al., 2024; Nnaji et al., 2021; Okunola et al., 2024 |
| Client demand | Market pressure to use technology to meet client safety expectations | Nnaji et al., 2021; Gonsalves et al., 2023; Gonsalves et al., 2024; Huang et al., 2021 |
| Cognitive load monitoring | Requiring little mental effort from users to operate and adapt to | Kim et al., 2018; Nnaji et al., 2021; Okpala et al., 2022; Okunola et al., 2024 |
| Compatibility with specific trades | Supporting trade-specific tasks without hindering movement or productivity | Awolusi et al., 2023; Gonslaves et al., 2023; Hondzinski et al., 2018; Okunola et al., 2024 |
| Corporate policy | Company commitment to support, fund, and regulate exo technology | Huan et al., 2021; Nnaji et al., 2021; Okpala et al. 2022 |
| Safety and health awareness | User education on health benefits to promote worker understanding | Choi et al., 2017; Gonslaves et al., 2023; Huan et al., 2021; Nnaji et al., 2021; Pillsbury et al., 2019 |
| Muscle activity reduction | Reduction of physical exertion through redistribution of loads. | Kim et al., 2018; Zheng et al., 2024 |
| Enhanced productivity and worker retention | Reduced physical strain leads to higher productivity | Awolusi et al., 2023; Gutierrez et al., 2024; Kim et al., 2024; Mahmud et al., 2022; Nnaji et al., 2021 |
| Training | Maximizing device benefits through structured teachings for proper fit, operation, and maintenance | Gonslaves et al., 2024; Mahmud et al., 2022; Nnaji et al., 2023; Okunola et al., 2024 |

| Drivers | Description | Sources |
|---|---|---|
| Expanded workforce accessibility | Enabling diverse participation in physically demanding tasks | Gutierrez et al., 2024; Shayesteh et al 2023 |
| Fatigue reduction and immediate pain relief | Safe and prolonged participation in otherwise strenuous tasks | Awolusi et al., 2023; Dobrucali et al., 2024; Gonslaves et al., 2024; Gonslaves et al., 2023; Gutierrez et al., 2024; Hondzinski et al., 2018; Kim et al., 2018; Nnaji et al., 2023 |
| Worker acceptance | Degree of embrace is enhanced by workers' comfort during use. | Gonslaves et al., 2024; Gutierrez et al., 2024; Kim et al., 2024; Nnaji et al., 2023; Okpala et al. 2022 |
| Long-term health benefits | Sustained reduction of MSD by minimizing strain | Awolusi et al., 2023; Huan et al., 2021; Okunola et al., 2024; Okpala et al. 2022 |
| Reduced worker compensation costs | Financial savings from fewer injuries and associated claims. | Okunola et al., 2024 |
| Supportive feedback | Real-time data collection to improve worker experience. | Awolusi et al., 2023 |

Awolusi et al. (2023) reiterated the prompt user feedback effect on using the technology for construction activities. It can be inferred that factors such as cognitive load monitoring, client demand for innovative safety measures, and integration of real-time user feedback were not considered as significant as other key drivers in the reviewed studies, despite their importance in enhancing the adoption of wearable exosuits. As a result of the effect of client demanding for the use of exoskeleton on site, there is a possibility that the completion cost of such projects might be higher and hence cost overrun. Conclusively, from the majority of studies, it is evident that the technology will present the workplace with safer, healthier, and more productive output, especially in the sector with extreme labor shortage among other issues.

*Barriers to exoskeleton adoption in US construction*

The review identified more than 15 barriers affecting exoskeleton adoption in the US construction industry. After reviewing for duplication and repetitions, the factors were pruned down to nine barriers to exoskeleton implementation in the construction industry as shown in Table 3. Table 3 presents a summary of studies that highlighted the barriers to exoskeleton adoption in US construction with specific factors highlighted. The barriers that exert the highest significance to exoskeleton adoption were determined by the number of studies that emphasized such barriers. The high implementation cost and associated operational cost are the biggest threats to exoskeleton adoption by construction companies (Gutierrez et al. 2024, Okpala et al. 2022). About nine studies recognized cost constraints to the adoption of exoskeletons in US construction. It is observed from studies that there is discomfort experienced in wearing an exoskeleton for long periods of time. In other to avoid duplication, discomfort, and difficulty in using exoskeleton for a long period were classified together as a significant barrier. In the same vein, the use of trackers and monitoring devices on the technology raises privacy issues which is one of the concerns of organizations. This assertion was highlighted by 9 publications as presented in Table 3.

Resistance to change from workers and management poses a significant barrier to the adoption and subsequent use of new technologies such as exoskeletons (Zheng et al. 2024, and Pillsbury et al. 2019). Cultural resistance to modern practices is a common problem faced within the construction industry as stakeholders tend to hold on to traditional approaches to doing things. The majority of the studies reviewed indicated cost constraints, discomfort, privacy issues, and resistance to change are the significant barriers to exoskeleton adoption in the US construction industry. Some of the other challenges to exoskeleton implementation include complexity of use, mobility restriction, training needs, and risk of being struck by objects. Despite the numerous benefits associated with the adoption of exoskeletons, strategies for overcoming the challenges revealed by various studies are significant in the use of the technology in US construction.

**Table 3.** Barriers to the Adoption of Exoskeletons in the US Construction Industry

| **Barriers** | **Description** | **Sources** |
|---|---|---|
| Compatibility issues | Movement restrictions, workflow disruptions, and integration with existing PPE | Nnaji et al., 2021; Gonslaves et al., 2024; Awolusi et al., 2023; Gonslaves et al., 2023; Pillsbury et al., 2019; Mahmud et al. 2022; Okpala et al. 2022 |
| Complexity of use | Intricate controls and a lack of intuitive design, increase mental strain | Nnaji et al., 2021; Shayesteh et al., 2023; Dobrucali et al., 2024 |
| Cost constraints | High initial purchase, limited budgets, and non-immediate ROI | Nnaji et al., 2021; Okunola et al., 2024; Gutierrez et al., 2024; Gonsalves et al., 2024; Dobrucali et al., 2024; Awolusi et al., 2023; Hondzinski et al., 2018; Huan et al., 2021; Pillsbury et al., 2019; Mahmud et al., 2022 |
| Discomfort | Irritation and unease will reduce the worker acceptance ratio. | Nnaji et al., 2021; Okunola et al., 2024; Gutierrez et al., 2024; Gonsalves et al., 2024; Hondzinski et al., 2018; Gonsalves et al., 2023; Pillsbury et al., 2019; Mahmud et al. 2022; Okpala et al. 2022 |
| Mobility and movement restriction | Possible limited range of motions for activities requiring agility | Kim et al., 2018; Gutierrez et al., 2024; Nnaji et al., 2023; Hondzinski et al., 2018 |
| Privacy concerns | Apprehensions about the use and storage of personal data generated | Nnaji et al., 2021; Choi et al., 2017; Dobrucali et al., 2024; Huan et al., 2021; Pillsbury et al., 2019; Mahmud et al., 2022 |
| Resistance to change | Workers, supervisors, or organizations reluctance to embrace new technology | Nnaji et al., 2021; Okunola et al., 2024; Nnaji et al., 2023; Gonsalves et al., 2024; Awolusi et al., 2023; Huan et al., 2021; Okpala et al. 2022 |
| Risk of catching and snagging | Potential for any protruding parts to get caught on machinery or tools | Okunola et al., 2024; Nnaji et al., 2023; Gonsalves et al., 2024; Zheng et al., 2024 |
| Training needs | Time, cost, and resources required for training increase organizational cost | Nnaji et al., 2021; Okunola et al., 2024; Gonsalves et al., 2024; Awolusi et al., 2023; Hondzinski et al., 2018 |

## Study Implication

The study contributes to the growing body of knowledge by providing a basis for comparing factors influencing exoskeleton adoption in the construction industry with other sectors. In the same vein, the study contributes to the growing literature on the barriers to adoption by framing the barriers as constructs. The scoping review provides comprehensive checklists of actionable steps towards increased adoption of exoskeletons in US construction. In the same vein, the study also presents a road map to policymakers, contractors, and safety managers on the drivers and barriers in order to make informed decisions on exoskeleton adoption in the construction industry in the US. Considering the significant barriers to exoskeleton implementation as highlighted in the study, the study provides the foundation for construction companies to take steps to reduce the effects of the barriers through structured training/education.

## Conclusion and Recommendations

The study provided a comprehensive understanding of the facilitators and inhibitors to exoskeleton adoption in US construction. The findings of the study showed that drivers such as reduction of fatigue, safety and health awareness, future standard equipment, compatibility to specific trades, and prevention of WMSDs have the potential to improve workers' safety and their overall height. The study also indicated that cost constraints, discomfort, privacy issues, and resistance to change are significant barriers to exoskeleton adoption in the US construction industry. The scoping review reiterates the need for strategic actions to overcome barriers and embrace the motivation factors for technology integration in the US construction industry. It is without a doubt that the adoption and use of exosuits come with numerous benefits, there is a need for top management commitment, education, and training about the use to improve the implementation. The study recommends that pilot programs be encouraged for specific work trades for exoskeleton implementation as against wholesale application in all construction trades or tasks. The gradual implementation will help gauge the process and take feedback for continuous improvement. It is important that construction organizations should promote a culture that embraces innovation and technology adoption among construction workers in the construction industry.

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