Heuristic Evaluations of Occupational Exoskeletons Using Universal Design Principles

Arunkumar Pennathur, PhD; apennathur@utep.edu

Physical, Information and Cognitive Human Factors Engineering (PIC-HFE) Research Laboratory, University of Texas at El Paso

Rising Workplace Injuries and the Promise of Exoskeletons

Concerning Statistics

Workplace injuries remain prevalent despite safety initiatives. The Bureau of Labor Statistics reports a steady injury rate of 2.7 per 100 full-time workers from 2021-2022, with total nonfatal injuries in private industry rising 7.5% to 2.8 million in 2022.

Exoskeleton Market Growth

The exoskeleton market is projected to reach $1.8 billion by 2025. In the EU, some exoskeletons have already received CE certification as personal protective equipment, with the US expected to establish similar regulations.

Research Momentum

Studies demonstrate exoskeleton effectiveness in both laboratory and limited field settings. Research shows how passive and active exoskeletons support performance in lifting, forward bending, and overhead construction activities.

Understanding Universal Design for Exoskeletons

Universal design ensures products are accessible to people with diverse abilities. For exoskeletons, this means accommodating workers of different ages, genders, and physical capabilities - increasing adoption rates and safety in industrial settings.

1. Equal Access

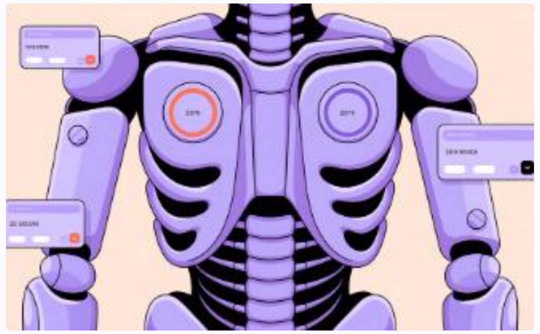
Design that serves diverse populations regardless of characteristics. With 40.3% of persons with disabilities in the workforce, exoskeletons must provide equitable support without requiring special accommodations.

2. Flexibility in Use

Features accommodating individual preferences through adjustable sizing, variable assistance levels, and adaptability to different tasks. Effective designs support both dominant and non-dominant hand use.

3. Simple and Intuitive

Easy to understand regardless of experience or language skills. Controls and operation should require minimal training, with interface elements that are consistent with user expectations and accommodate varied literacy levels.



4. Perceptible Information

Essential information communicated through multiple modes (visual, tactile, audio). Status indicators for power levels, operational modes, and malfunctions should be legible in various environments.

Understanding Universal Design for Exoskeletons

Universal design ensures products are accessible to people with diverse abilities. For exoskeletons, this means accommodating workers of different ages, genders, and physical capabilities - increasing adoption rates and safety in industrial settings.

5. Tolerance for Error

Features that minimize hazards from accidental actions. Critical as 45% of workers will be aged 45+ by 2032. Designs should include warnings and fail-safe features that protect users if components fail.

6. Low Physical Effort

Designs that can be used efficiently with minimal fatigue. Exoskeletons should maintain neutral body positioning, use reasonable operating forces, and minimize repetitive actions - fulfilling their core purpose of reducing physical strain.

7. Size and Space for Approach and Use

Appropriate dimensions for all body sizes and mobilities. Features include clear lines of sight, comfortable reach to components, and accommodations for varied hand sizes. Storage and transport considerations are crucial for industrial implementation.

The Importance of Basic Tasks Beyond Active Use

Assembly

Putting together the exoskeleton from its stored state into a wearable configuration. This involves connecting parts, adjusting sizes, and preparing the device for donning.

Donning

Placing the assembled exoskeleton correctly on the body. This includes securing straps, aligning the device with body parts, and making final adjustments for comfort and function.

Doffing

Removing the exoskeleton from the body after use. This includes loosening straps, disconnecting parts from the body, and transitioning to disassembly.

Disassembly

Taking apart the exoskeleton for storage, cleaning, or transport. This involves disconnecting components, organizing parts, and preparing for future use or storage.

Study Methodology: Heuristic Evaluation Process

Planning and Orientation

The team established protocols, selected exoskeletons, and developed criteria based on universal design principles. Seven human factors engineering experts received orientation on the study approach.

Evaluation and Rating

Evaluators independently assessed four exoskeletons across assembly, donning, doffing, and disassembly tasks, documenting problems related to universal design criteria.

Discussion and Reconciliation

The team reviewed divergent ratings, focusing on extremes. This process enabled evaluators to explain their reasoning and adjust ratings based on collective insights.

Analysis and Documentation

Compiled ratings were analyzed to identify patterns, problematic design elements, and strengths across the evaluated exoskeletons.

Exoskeletons Evaluated in the Study

Back-Support Exoskeleton

The Laevo Flex is a passive lumbar-flexion-support device designed to reduce strain during bending and lifting tasks. It provides mechanical assistance to the lower back through a system of supports and springs that distribute forces away from vulnerable spinal structures.

Shoulder-Support Exoskeleton

The Skelex is a passive device intended to reduce fatigue when workers perform activities above shoulder height. It uses mechanical assistance to support the arms in elevated positions, potentially reducing strain on shoulder muscles during overhead work.

Handgrip-Strength Exoskeleton

The Ironhand is an active exoskeleton powered by a battery pack. It enhances grip strength through sensors on the palm and fingers that activate when the user grasps objects, providing additional force to reduce hand and forearm fatigue.

Sit-Stand Support Exoskeleton

The Chairless Chair allows workers to alternate between sitting, standing, and walking without requiring a physical chair. This passive device locks into position when activated, creating a supportive structure that reduces fatigue during prolonged standing.

Universal Design Criteria and Rating System

Rating	Description
1	Not at all - The design completely fails to meet this criterion
2	Poor - The design meets this criterion minimally with significant issues
3	Moderate - The design adequately meets this criterion with some issues
4	Good - The design meets this criterion well with minor issues
5	Excellent - The design fully meets this criterion with no issues

The evaluation team used seven principles of universal design, converting each guideline into question format to simplify evaluation. Ratings were assigned on a 1-5 Likert-type scale, with 1 representing "not at all" meeting the criterion and 5 representing "excellent design." This approach allowed for consistent evaluation across different exoskeletons and tasks.

To ensure rating consistency, the team developed rules for identifying when ratings diverged significantly enough to warrant discussion. These discussions allowed evaluators to explain their perspectives and potentially revise ratings based on shared insights.

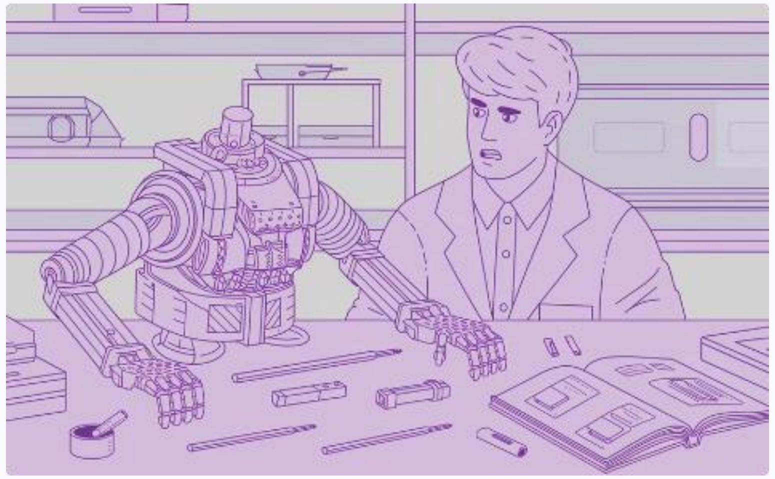
Key Findings: Poorly Rated Design Principles

Perceptible Information

Exoskeletons often failed to provide clear feedback and information to users. Sizing information was frequently illegible or relied solely on color coding, making it difficult for users with visual impairments to identify proper fit. Assembly sequences were often unclear, requiring users to consult manuals that themselves contained limited information.

Equitable Use

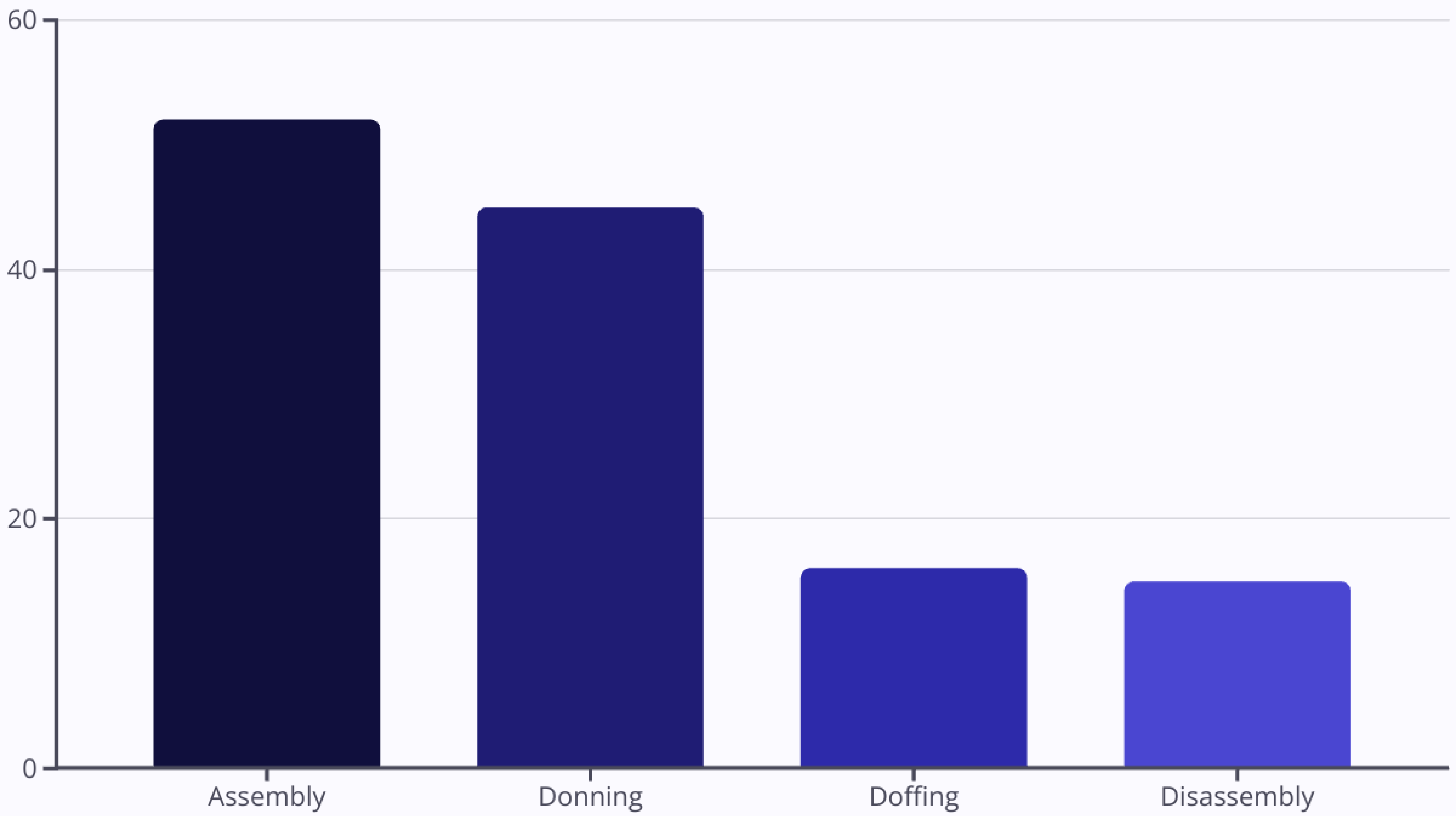
Most exoskeletons were not designed for universal accessibility. The sit-stand and shoulder-support exoskeletons presented safety concerns during donning, with balance challenges and potential collision hazards. Device weight and complex assembly requirements created barriers for users with limited mobility or strength.



Simple and Intuitive Design

Assembly and donning procedures were often complex and non-intuitive. Many exoskeletons contained numerous components that complicated assembly, requiring special tools and flat surfaces. The complexity of parts and connections created cognitive load that could be particularly challenging for first-time users.

Task-Specific Evaluation Results



Assembly and donning tasks accounted for approximately 76% of all identified universal design criteria violations across the four exoskeletons. These initial interaction phases presented the greatest challenges to users, with numerous issues related to information clarity, physical requirements, and intuitive design. In contrast, doffing and disassembly tasks presented fewer issues, as they often involved reversing earlier steps.

The higher number of violations during assembly and donning is particularly concerning as these tasks must be completed successfully before an exoskeleton can be used for its intended purpose. Barriers at these stages could significantly impede workplace adoption.

Most Frequently Violated Universal Design Criteria

User Sensory Limitations

Exoskeletons frequently failed to consider diverse sensory abilities. Visual information was the primary means of conveying critical details like sizing and assembly steps, with limited tactile or auditory alternatives.

Informative Feedback

Devices often lacked clear feedback mechanisms to indicate correct assembly, proper fit, or successful connections between components. Users had to rely on visual inspection or trial and error.

Equal Means of Use

Many exoskeletons did not provide equivalent usage options for diverse users. Strength and dexterity requirements created barriers for users with different physical capabilities.

These findings highlight fundamental accessibility issues that could limit the potential benefits of exoskeletons for a diverse workforce. Addressing these criteria could substantially improve user experience and adoption rates across different worker populations.

Positively Rated Design Aspects

Minimal Memory Requirements

The sit-stand exoskeleton earned high ratings for minimizing memory load during assembly. Parts resembled body shapes, making memorization of assembly steps unnecessary. Clear visual cues reduced cognitive burden, allowing users to follow intuitive patterns rather than memorizing sequences.

Reduced Physical Effort

Several exoskeletons performed well in minimizing repetitive actions and requiring reasonable operating forces. The back-support exoskeleton received high marks for ensuring operating forces were reasonable during donning, and for minimizing sustained physical effort once properly fitted.

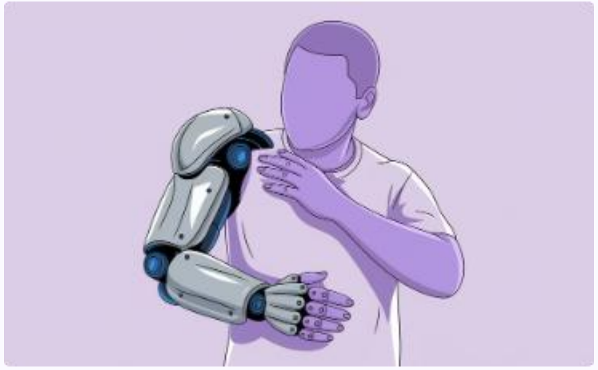
User Control and Flexibility

The shoulder-support exoskeleton provided adjustable features for diverse users during donning. The handgrip exoskeleton allowed users to assemble at their own pace without constraints. These flexibility features enhanced user autonomy and accommodated different physical capabilities.

Safety Concerns During Assembly and Donning

Balance Issues

The sit-stand exoskeleton requires users to maintain balance while donning and attempting to sit on seat pads. The device's weight increases falling risk when bending to secure it to the feet, especially if users combine assembly with donning.



Collision Hazards

With the shoulder-support exoskeleton, evaluators noted safety risks of accidentally hitting themselves with unanticipated bouncing and ricochet of the arm-cup assembly during donning. Moveable parts could unexpectedly contact users.

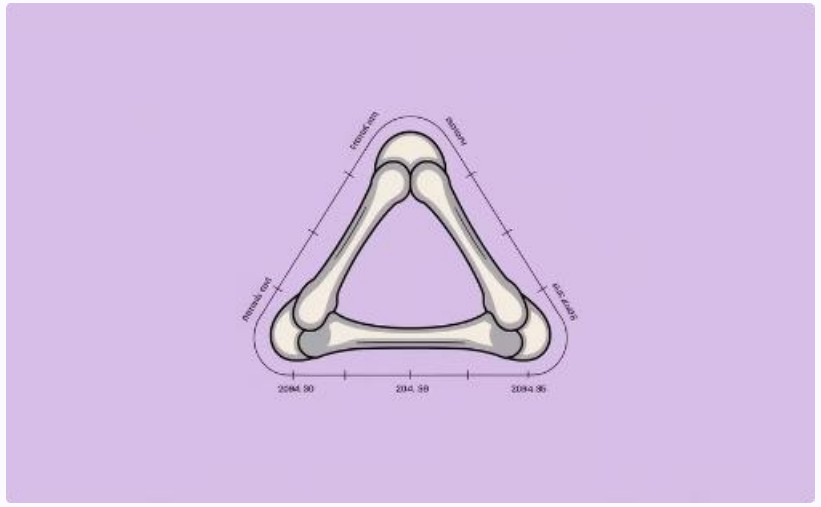
Stability Problems

The sit-stand exoskeleton does not stand upright without support, requiring users to hold the device while simultaneously securing it to their body, creating a potentially hazardous situation requiring coordination and strength.

Accessibility Barriers

Exoskeletons generally were not usable by workers with disabilities or those using assistive devices like canes. The strength and balance requirements created significant barriers for users with mobility limitations.

Information Design and Feedback Challenges



Illegible Information

Sizing information was often printed in small text or color-coded on thin parts, making it difficult for users to determine proper fit. Color-coding created additional barriers for users with color vision deficiencies who could not differentiate between certain colors.

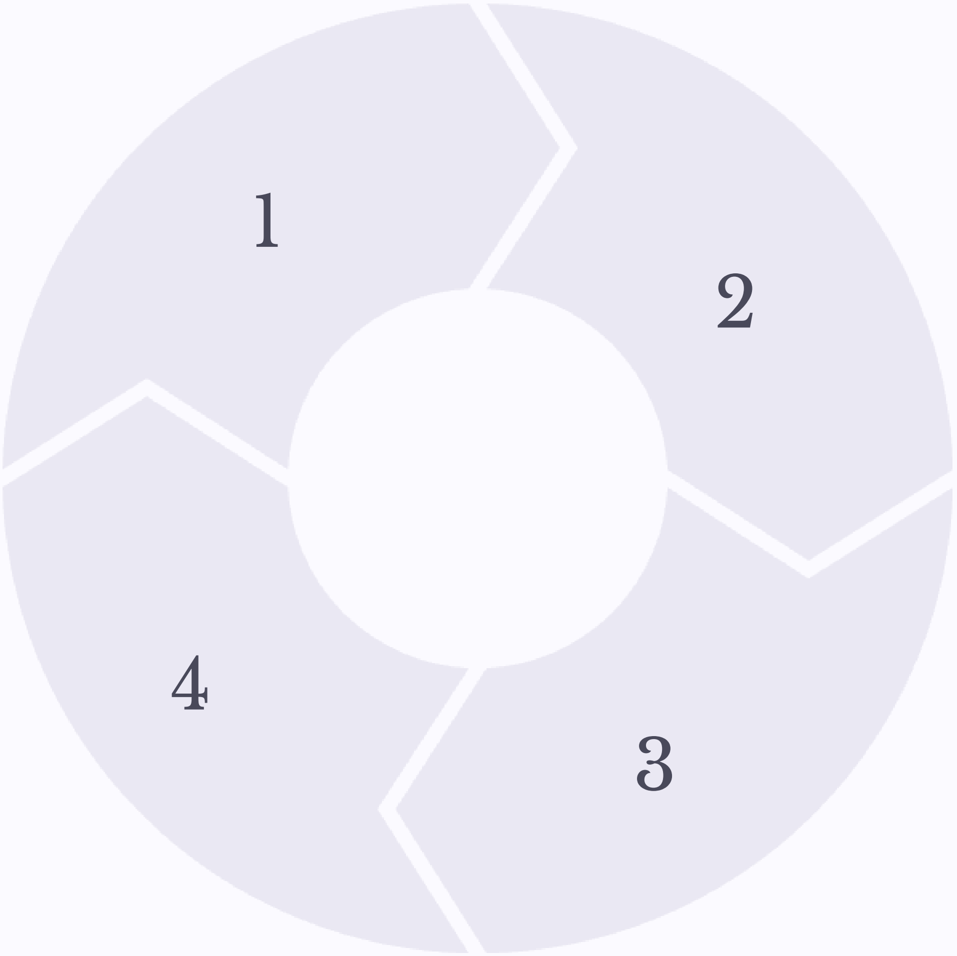
Complex Assembly

Exoskeletons often contained numerous components without clear assembly sequences. Users had to rely on manuals that themselves contained limited information. The lack of constrained connections between parts allowed for incorrect assembly without feedback.

Limited Feedback

Devices rarely provided clear feedback on correct assembly, fit, or operation. Users had to rely on visual inspection or trial and error to determine if components were properly connected or if the device was correctly positioned on the body.

Exoskeleton-Specific Design Issues



Back-Support

Illegible sizing information, excessive parts requiring strength to connect, and lack of feedback during assembly

Shoulder-Support

Collision hazards during donning, arm rebound risks, and chest strap designs unsuitable for female users

Handgrip-Strength

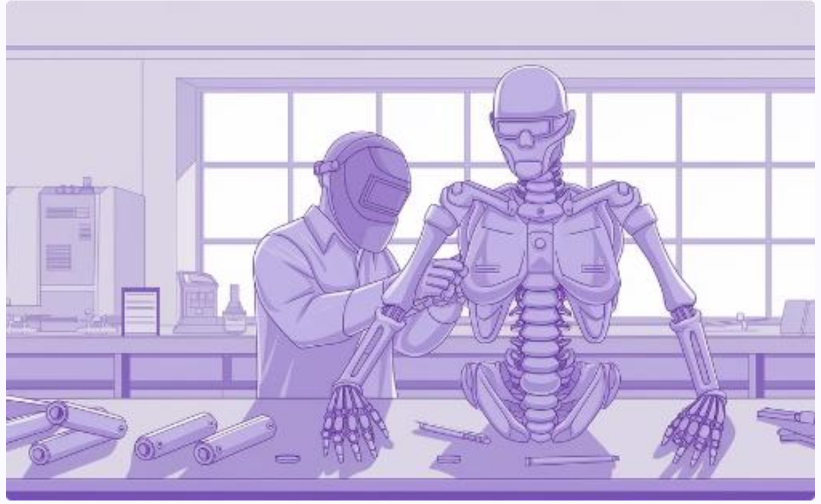
Limited feedback on proper operation, battery connection issues, and unclear glove sizing information

Sit-Stand

Balance challenges during donning, stability issues when not worn, and high physical demands for assembly

Each exoskeleton presented unique design challenges that could impact usability and accessibility. While the handgrip-strength exoskeleton generally received the highest ratings, it still presented issues with feedback and information clarity. The back-support and sit-stand exoskeletons posed particular challenges during assembly and donning phases.

Design Considerations for Future Exoskeletons



Pre-use and Post-use Task Evaluation

Consider assembly, donning, doffing, and disassembly as core user experience elements. These activities require the same evaluation rigor as primary functional tasks. Implement partial pre-assembly or simplified connections to reduce user burden.

User-Exoskeleton Interaction Points

Design interaction points for intuitive use and clear feedback. Incorporate locking mechanisms that provide sensory confirmation of correct assembly. Improve visual access to connections worn on body areas with limited visibility.

Diverse User Populations

Accommodate workers with varying physical capabilities, including those with disabilities. Apply rehabilitation exoskeleton design principles to occupational models. Create documentation that addresses different literacy levels, educational backgrounds, and sensory abilities.

Safety Design for Exoskeletons

1. Eliminate Hazards

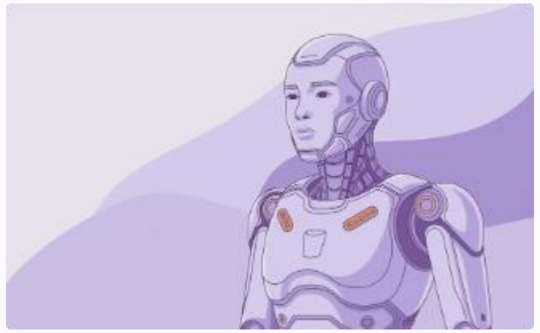
Remove unnecessary parts or processes that create safety risks

2. Design Safety Features

Build in constraints that prevent incorrect assembly or dangerous movements

3. Provide Warnings

Add clear indicators for potential hazards or incorrect usage



4. Develop Procedures

Create step-by-step instructions with emphasis on safety considerations

5. Train Users

Ensure proper education on safe handling and operation

In-Situ Implementation Factors

Beyond design considerations, successful implementation of exoskeletons in workplace settings depends on numerous practical factors. Storage space requirements for assembled or partially assembled devices may limit availability in space-constrained environments. The need for assistance during donning and doffing could require additional personnel resources or buddy systems.

Cleaning and sanitization protocols become particularly important when devices are shared among multiple workers. Training requirements and the learning curve for proper assembly and use must be factored into implementation timelines. These practical considerations should inform both design decisions and workplace implementation strategies.

Barriers to Industrial Adoption

Cost Factors

High exoskeleton costs limit adoption, especially when customization is needed. Additional expenses for training, maintenance, and support staff further impact implementation feasibility.

User Perception

Potential users may view exoskeletons as unnecessary or stigmatizing. Older workers often associate assistive devices with declining health, creating psychological resistance despite benefits.

Safety Concerns

Lack of consensus on effectiveness and safety hinders acceptance in safety-conscious industrial settings. Without established guidelines, companies hesitate to implement due to liability risks.

Training Requirements

Specialized training for assembly, donning, use, and maintenance creates implementation challenges, especially in environments with high turnover or temporary workforces.

Research Limitations and Future Directions

Heuristic Evaluation Limitations

This study used heuristic evaluation rather than testing with diverse users. While efficient for identifying design issues, it may miss real-world challenges faced by workers with varying abilities and limitations.

Limited Exoskeleton Sample

The evaluation of only four exoskeletons represents a small segment of the market. As designs evolve from soft to rigid constructions, broader assessment will be necessary.

Focus on Basic Tasks

While the study examined critical assembly, donning, doffing, and disassembly tasks, comprehensive evaluation should also address adoption barriers including training needs, costs, and workplace integration.

Conclusion: The Path Forward for Universal Exoskeleton Design

Enhanced Accessibility

Future exoskeletons must consider a broader user base, including workers with disabilities, older workers, and women. Designs should accommodate diverse anthropometrics, strength levels, and potential limitations.

Safety Improvements

Critical safety concerns during assembly and donning must be addressed through improved design constraints, feedback mechanisms, and stabilizing features that prevent falls or collisions.

Simplified Operation

Designs should move toward one-person operation with intuitive assembly sequences, clear feedback, and minimal parts that require limited strength or dexterity to manipulate.

Implementation Support

Industry barriers such as training needs, storage requirements, and device customization should be considered early in the design process to facilitate widespread adoption.

References

Alejandra Martinez, Laura Tovar, Carla Irigoyen Amparan, Karen Gonzalez, Prajina Edayath, Priyadarshini Pennathur & Arunkumar Pennathur (14 Mar 2025): Heuristic Evaluations of Back-Support, Shoulder-Support, Handgrip-Strength Support, and Sit-Stand-Support Exoskeletons Using Universal Design Principles, **IISE Transactions on Occupational Ergonomics and Human Factors**, DOI: https://doi.org/10.1080/24725838.2025.2476438

Martinez, A., Tovar, L., Amparan, C. I., Gonzalez, K., Edayath, P., Pennathur, P., & Pennathur, A. (2024). Usability of an Active Hand Grip Strength Industrial Exoskeleton: A Heuristic Evaluation. **Proceedings of the Human Factors and Ergonomics Society Annual Meeting**, 68(1), 1855-1860. https://doi.org/10.1177/10711813241260674 (Original work published 2024).