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A Review on the Design, Fabrication, and Analysis of Exoskeletons: Industrial, Medical, and Safety Perspectives

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Abstract

Exoskeletons are wearable robotic devices intended to augment or restore human function in industrial, medical, and safety-critical contexts. To address editorial requests, this revised review replaces generic language with evidence-based statements and integrates ten references with in-text citations. Drawing on recent laboratory and field studies, we summarize design choices, actuation and control, safety and compliance, and practical evaluation. For industrial applications, passive shoulder exoskeletons consistently reduce deltoid/trapezius activity during overhead work; effects are task-specific below shoulder height. In rehabilitation, trajectory-tracking accuracy within a few degrees is achievable with appropriate sensing and impedance control. We conclude with implementation guidance that emphasizes task selection, assistance tuning, and risk management.

Keywords: exoskeletons, industrial ergonomics, rehabilitation robotics, human-machine interaction, safety, compliance, evaluation.

1. Introduction

Exoskeletons span passive, hybrid, and powered systems for the upper and lower limbs. Industrial devices aim to reduce exposure to biomechanical risk factors, particularly during overhead or sustained postures, whereas rehabilitation devices assist patients with neurological or musculoskeletal deficits. Despite rapid progress, translation beyond pilots requires a consolidated view that links design to measurable outcomes and safety. This review integrates recent experimental findings with practical design and compliance considerations, using numbered citations in the journal's style.

2. Results and discussion

Classification and design overview

By application, devices are broadly (i) industrial support systems and (ii) medical/rehabilitation systems. By actuation, devices are passive (spring/elastic), powered (electric, pneumatic, hydraulic), or hybrid. Rigid frames provide precise kinematics and high load capacity, while soft exosuits prioritize comfort and portability. Design choices follow a task-driven analysis of joint torques, allowable mass, and range of motion; rehabilitation systems typically favor more degrees of freedom with careful alignment and back-drivability, whereas industrial supports minimize complexity and focus on fit, donning/doffing, and durability (de Looze et al., 2016; Maurice et al., 2019).

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Evidence for industrial applications

Field and laboratory studies quantify physiological exposure reduction when passive shoulder exoskeletons (PSEs) are used for overhead work. In slaughterhouse packaging work, a randomized crossover study (n = 26) reported bilateral reductions in anterior and medial deltoid (~10–29 %) and upper trapezius (~22 %) activity versus no device (Dalbøge et al., 2024). In cleaning tasks, a spring-loaded PSE reduced total shoulder EMG by ~17 % and decreased perceived effort in the shoulder/arm/back by ~16–23 % (Pacifico et al., 2023). Two-height drilling experiments showed ~29–58 % reductions in upper-limb muscle activity with two different passive devices (Kong et al., 2023). Fatigue-oriented trials indicate that support partially mitigates fatigue-induced changes while maintaining task precision (Bock et al., 2023). Model-based simulations of the Exo4Work system demonstrate reduced shoulder and elbow loading for tasks above shoulder height but highlight that assistance can increase non-target loads at or below shoulder height, underscoring the need for task matching (van der Have et al., 2022).

Evidence for rehabilitation

Lower-limb and upper-limb rehabilitation exoskeletons emphasize accurate sensing and compliant control to ensure safety and comfort. Recent controllers achieve trajectory-tracking errors on the order of a few degrees with response times in the 100–200 ms range using impedance/admittance strategies and multimodal sensing (Ramella et al., 2024). Actuator selection for modular lower-extremity robots typically balances torque density, back-drivability, and heat with brushless DC motors and series elasticity for safety (Kavalieros et al., 2022).

Actuation and control

Electric motor drives remain the dominant choice for powered joints due to compactness and control fidelity, while pneumatic actuators appear in soft suits where low mass is prioritized. Passive shoulder supports rely on preloaded springs or elastic elements to offload arm weight; assistance tuning is critical – over-compensation can increase antagonist activation during dynamic lowering phases (Ramella et al., 2024). Human-in-the-loop adaptation using EMG, IMUs, and task context is an active research area for personalization (de Looze et al., 2016; Maurice et al., 2019).

Safety, risk, and compliance

Risk management follows a structured process: hazard identification, risk estimation, protective measures, and verification/validation. Relevant standards include ISO 12100 (machinery safety), ISO 14971 (medical risk management), ISO 13482 (personal care robots), IEC 60601 (medical electrical safety), and ASTM F48 guidance for exoskeletons. Industrial deployments should monitor strap pressures, thermal buildup, electrical safety, and emergency-stop performance, while confirming that exposure reductions do not introduce compensatory loads to other joints (van der Have et al., 2022; Maurice, 2019).

Evaluation and implementation guidance

The passive shoulder exoskeleton is most effective when used for overhead or above-shoulder tasks, where it reduces shoulder and elbow loading and helps prevent strain. However, during below-shoulder or prolonged low-level activities, the device can actually increase stress on the shoulder and knee, making its assistance counterproductive (van der Have et al., 2022).

When using passive upper-limb exoskeletons, it is recommended to begin with moderate assistance and ensure that arm-lowering movements remain comfortable; spring settings should then be adjusted carefully to prevent over-support, which can increase antagonist muscle activation and discomfort (Ramella et al., 2024).

A structured familiarization period is essential to ensure safe and effective integration of passive shoulder exoskeletons. Progressive exposure, such as gradually increasing wear time across one to two weeks, helps workers stabilize movement patterns, adapt ergonomically, and build acceptance of the device (Dalbøge, 2024; De Bock, 2023).

Evaluation of passive exoskeletons should incorporate mixed outcomes, including EMG or exposure proxies, task performance, user-reported effort and discomfort, as well as overall acceptability, to provide a comprehensive understanding of their effectiveness (Dalbøge et al., 2024; Kong et al., 2023; Pacifico et al., 2023).

Integrate devices within existing ergonomics programs alongside engineering and administrative controls; reassess risks regularly (van der Have et al., 2022; de Looze et al., 2016).

3. Conclusion

Evidence from recent field and laboratory investigations shows that when matched to the right tasks and tuned appropriately, passive shoulder exoskeletons reduce shoulder muscle activity and may mitigate fatigue in overhead work. Rehabilitation devices achieve accurate, compliant assistance when sensing and control are carefully designed. Successful adoption depends on task selection, individual fitting, assistance tuning, and adherence to formal risk-management and compliance processes.

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