Exoskeleton Technology in Agriculture — Comprehensive Overview, Classification, and Research Insights

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Abstract

Agricultural labor, especially in India, remains physically demanding with significant risks for musculoskeletal disorders due to repetitive manual tasks such as load carrying, bending, and prolonged awkward postures. Exoskeleton technology—wearable mechanical devices that offload physical stress and support human movement—has emerged as a promising ergonomic intervention. This article provides a comprehensive overview of exoskeleton types, design considerations, ergonomic benefits, challenges in adoption, and future directions with a focus on the diverse Indian agricultural context. Scientific evidence from electromyography studies and field trials is discussed, alongside emerging innovations integrating artificial intelligence and sensor technology for adaptive assistance. The future of agricultural exoskeletons is envisioned as integral to smart farming ecosystems, promising transformative impacts on worker health, productivity, and labor sustainability across India's heterogeneous landscapes.

1. Introduction: The Physical Burden of Agricultural Labor

Agricultural work remains one of the most physically demanding professions, involving repetitive manual labor such as lifting, carrying heavy loads, stooping, bending, and prolonged awkward postures. These activities place significant mechanical stress on the musculoskeletal system, rendering workers especially vulnerable to work-related musculoskeletal disorders (WMSDs), including chronic back pain, joint degeneration, and repetitive strain injuries (Upasani et al., 2019). Unlike many other sectors, agriculture often requires uninterrupted labor during peak seasons despite injury or fatigue, intensifying health risks and reducing productivity (Virginia Cooperative Extension, 2023).

This physical burden is exacerbated in terrains marked by hills or mountains—common in many agricultural regions—where mechanized aids are limited or unavailable. Manual load carrying on steep or uneven grounds increases biomechanical stress on the spine, shoulders, and lower limbs, elevating risks of fatigue and injury (Ergonomics Evaluation of Exoskeletons in Agriculture, 2023). These factors underscore the urgent need for ergonomic interventions that alleviate physical strain without compromising farm productivity.

2. What is an Exoskeleton and Why Is It Needed?

An exoskeleton is a wearable external mechanical device designed to augment the human musculoskeletal system by redistributing physical loads, stabilizing posture, and reducing muscle fatigue. It functions as an artificial support framework that offloads stresses from vulnerable areas such as the spine, hips, knees, and shoulders. By mitigating biomechanical load during tasks like lifting, carrying, bending, and walking with heavy loads, exoskeletons lower musculoskeletal injury risk and enhance comfort and endurance (D'Souza et al., 2020).

Farmers working in rugged agricultural landscapes rely heavily on manual labor involving load carrying across challenging terrains, which imposes excessive biomechanical strain and heightens the prevalence of work-related musculoskeletal disorders (Srinivasan et al., 2020). Well-designed exoskeletons specifically tailored for agricultural conditions integrate modular frames to transfer upper body loads to the legs, adjustable straps for customized fitment, and rugged construction suited for fieldwork (Srinivasan et al., 2020).

3. Classification of Agricultural Exoskeletons

Exoskeletons are categorized based on actuation, supported body regions, and application modes.

i. Actuation Types:

1. **Passive Systems:** Utilize springs, elastic bands, or mechanically stored energy for assistance without relying on motors. Favored in agriculture for their lightness, simple maintenance, and field reliability (Arachchige et al., 2024).

2. **Active Systems:** Include motors and sensors for dynamic, powered assistance, offering higher force but greater complexity and weight (Choi, 2025).
3. **Hybrid and Pseudo-Passive:** Combine mechanical elements with limited active control to optimize support and usability.

Fig. 1. Types of Agricultural Exoskeletons and Their Characteristics

ii. Body Region Support

1. **Upper Limb:** Supports shoulders, arms, and back for tasks like pruning or spraying.
2. **Lower Limb:** Assists hips, knees, and legs in load bearing and posture stabilization.
3. **Full-Body:** Provides integrated support across both upper and lower body.

Table1. Types of Agricultural Exoskeletons and Their Characteristics

Exoskeleton Type	Actuation	Body Region Supported	Advantages	Challenges
Passive Upper Limb	Passive	Upper Limb	Lightweight, simple, reliable	May restrict movement
Passive Lower Limb	Passive	Lower Limb	Reduces spinal load, durable	Fit and comfort issues
Active Full Body	Active	Full Body	Dynamic support, high force	Heavy, requires power source
			assistance	
Hybrid Semi-Active	Hybrid	Varies	Balanced assistance, adaptable	Cost and complexity
Stationary Support	Passive	Postural	Supports static tasks, reduces fatigue	Limited mobility
Mobile Support	Passive	Dynamic Tasks	Allows mobility, ergonomic assistance	Energy storage and transfer limitations

iii. Application Modes

- **Stationary:** Designed for fixed postures during tasks.
- **Mobile:** Facilitate natural walking and dynamic movement over uneven terrain.

4. Design Considerations and Features

Effective agricultural exoskeletons incorporate:

- **Biomechanical Load Transfer:** Efficiently shift loads from spine to lower limbs to reduce spinal compression, validated by biomechanical modeling studies showing up to 40-50% force reduction during load carrying (Srinivasan et al., 2020).
- **Adjustability and Comfort:** User-customizable straps and frames to accommodate diverse body types and maintain natural movement.
- **Ruggedness:** Durable materials to withstand agricultural environmental challenges without sacrificing comfort.
- **Lightweight Passive Mechanism:** To ensure prolonged use without additional fatigue from device weight.

Computer-aided design and iterative field validations align these parameters with real-world agricultural demands (Srinivasan et al., 2020).

5. Ergonomic and Physiological Benefits

Research demonstrates multiple benefits of exoskeletons in agriculture:

1. EMG studies by Thamsuwan et al. (2020) show passive lower-back exoskeletons reduce erector spinae muscle activity by over 50%, lowering fatigue during heavy load tasks.
2. Le and Lin (2025) evaluated a 3D-printed exoskeleton revealing a 55-64% reduction in lower limb muscle fatigue in greenhouse tomato harvesting.
3. Heart rate monitoring confirms reduced cardiovascular load during lifting with exoskeleton support, corroborated by subjective perceived exertion decreases (Ergonomics Evaluation of Exoskeletons in Agriculture, 2023).
4. However, ergonomic research also notes that upper limb exoskeletons can result in increased load in compensatory areas, emphasizing the need for comprehensive biomechanical assessment (Choi, 2025).

By mitigating muscle loading, exoskeletons contribute to injury prevention and enhanced work capacity. These findings illustrate the transformative potential of exoskeletons for agricultural health and productivity.

6. Challenges and User Experience

Adoption challenges for agricultural exoskeletons encompass several critical factors. Ergonomic fit and comfort are paramount; ill-fitting devices can cause discomfort or restrict natural movement, which diminishes their effectiveness and user acceptance. The complexity of agricultural tasks and variability in worker physiques necessitate highly customizable and adaptable exoskeleton designs. Additionally, there is a learning curve associated with effective exoskeleton use, requiring adequate training and familiarization to maximize benefits and avoid misuse or injury. Economic barriers present significant obstacles, as the cost of exoskeleton technology may be prohibitive for many smallholder farmers or low-resource agricultural communities. Furthermore, the diverse range of agricultural activities demands versatile devices capable of accommodating varying postures and tasks without impeding productivity. Despite these challenges, farmers and users interviewed in studies recognize reductions in work-related pain and fatigue, underscoring that ease of use and affordability are key determinants for broader acceptance and long-term adoption (D'Souza et al., 2020)

7. Future Directions: Smart Exoskeletons and Digital Agriculture in India

The future of agricultural exoskeletons is shaped by advancements in sensor technology, artificial intelligence (AI), and integration within digital farming ecosystems—factors especially relevant to Indian agriculture characterized by smallholder farmers and diverse terrains.

Emerging exoskeletons embed arrays of sensors such as inertial measurement units (IMU), force, pressure, and electromyography (EMG) sensors to capture real-time biomechanical and physiological data. AI algorithms analyze this data to dynamically adjust assistance, providing real-time adaptive support that aligns with user fatigue, posture, and task intensity. This makes exoskeletons more effective and comfortable during long working hours typical in India (MarketsandMarkets, 2024; Tiboni et al., 2022).

Integration with India's growing digital agriculture platforms offers opportunities for remote health monitoring, performance optimization, predictive device maintenance, and ergonomic evaluation at farm and community scales. Internet of Things (IoT) connectivity allows exoskeleton data to complement broader precision agriculture initiatives, thereby supporting sustainable productivity and worker well-being (TechNalia, 2025).

Beyond traditional load carrying, new applications are expanding to horticulture pruning, tea and coffee plucking, manual spraying, and planting. Adaptation of exoskeletons for these tasks is underway in Indian research, mindful of cultural, climatic, and socio-economic nuances.

Challenges to broad adoption include affordability, maintenance in rural settings, training accessibility, and design adaptability to India's heterogeneity of labor conditions. Strong collaboration among research institutions, government programs, and private sector innovation is crucial to overcome these barriers and promote inclusive innovation (D'Souza et al., 2020).

8. Conclusion

Exoskeleton technology offers transformative potential to alleviate the physical burdens of agricultural labor, especially in challenging terrains familiar to India and many developing countries. By effectively redistributing biomechanical loads, reducing injury risks, and enhancing worker comfort and safety, these devices promise to foster sustainable and

productive agricultural systems. Future developments integrating AI and digital ecosystems will further augment their efficacy, making ergonomic enhancement accessible to a broader spectrum of farmers and improving rural livelihoods.

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