LETTER

OPEN ACCESS

Journal homepage: www.the-innovation.org/energy-use

Energy Use

Energy Use 1 (2026):100032

Contents lists available at INNOVATION PRESS

Powering Humanoid Robots: The Central Role of Battery Technology

Jiaojiao Deng,[1] Junquan Chen,[1] and Jinhan Mo[1,2,3,*]

[1]Key Laboratory of Coastal Urban Resilient Infrastructures (Ministry of Education), College of Civil and Transportation Engineering, Shenzhen University, Shenzhen 518060, China

[2]State Key Laboratory of Subtropical Building and Urban Science, Shenzhen University, Shenzhen 518060, China

[3]Key Laboratory of Coastal Urban Soil-Water Environmental Evolution, Ministry of Ecology and Environment (under construction), Shenzhen University, Shenzhen 518060, China

*Correspondence: mojinhan@szu.edu.cn

Received: February 4, 2026; Accepted: March 13, 2026; Published Online: March 25, 2026; https://doi.org/10.59717/ipj.energy-use.2026.100032

© 2026 The Author(s). This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by/4.0/).

Citation: Deng J., Chen J. and Mo J. (2026). Powering Humanoid Robots: The Central Role of Battery Technology. *Energy Use* **2**:100032.

Recent advancements in artificial intelligence (AI), sensing, and mechanical systems have substantially expanded the functional capabilities of humanoid robots. However, their transition from laboratory demonstrations to sustained real-world operation remains fundamentally limited by onboard energy storage. Battery technology now represents a primary system-level constraint, shaping achievable runtime, mobility, and operational reliability. Humanoid robots place unusually demanding requirements on batteries, combining high energy density, robust power output, and stringent safety within severe mass and volume constraints. Current lithium-ion batteries (LIBs) struggle to satisfy these competing demands, leading to restricted endurance, thermal management challenges, and conservative operating envelopes. In this perspective, we identify battery systems as a central bottleneck in humanoid robotics and contend that meaningful progress will require coordinated innovation across materials, power-system architectures, and battery management. Emerging approaches, including high-energy-density cells, higher-voltage platforms, distributed and hybrid power architectures, and AI-driven battery management systems (BMS), offer pathways to extend operational duration while improving mobility and robustness. Advances in battery technology will therefore play a decisive role in enabling scalable, reliable humanoid robots for industrial and societal applications.

INTRODUCTION

Humanoid robots are autonomous systems with human-like forms and intelligent decision-making. They perform tasks in complex, human-centred environments that demand adaptability, operational flexibility, and intuitive interaction with people.[1] Unlike traditional industrial robots, which are usually fixed and programmed for specific jobs, humanoid robots use existing spaces, tools, and infrastructure designed for humans, enabling seamless collaboration.[2] Recent progress in platforms like Tesla Optimus and Boston Dynamics Atlas shows humanoid robots moving from lab research to real-world use.[3]

Progress in artificial intelligence (AI), deep learning, advanced materials, sensors, and computing hardware has driven recent advances in humanoid robotics. However, as tasks evolve from simple mobility to complex, dynamic manipulation and interaction, the domain of energy storage and power delivery emerges as the most formidable barrier to effective and scalable deployment. Unlike stationary equipment or even electric vehicles (EVs) with relatively generous packaging space, humanoid robots require an ultra-compact, lightweight, and high-capacity power source to sustain whole-body, multi-degree-of-freedom motion for extended periods.[4] The battery system, therefore, is not merely a component but a defining subsystem that directly determines a robot's mobility range, functional endurance, safety protocols, and overall capability envelope, making it a decisive factor in the success or limitation of any practical humanoid system.

Presently, lithium-ion batteries (LIBs) serve as the incumbent and primary energy storage technology for humanoid robots, owing to their favourable balance of high energy density, respectable power density, and proven cycle life.[5] Mature manufacturing ecosystems and broad market availability further support supply chain stability and potential for cost reduction at scale. However, current LIBs fall short of meeting the holistic operational requirements for next-generation humanoid applications. Typical operational endurance remains confined to a modest 2 to 4 hours for moderate activity, which is insufficient for full-day work shifts or extended missions. Physically demanding tasks, such as rapid locomotion, lifting heavy payloads, or recovering from perturbations, induce high-current pulses. This leads to significant ohmic heating, accelerated degradation, and heightened safety risks, especially within confined enclosures.[6] Furthermore, the irregular, space-constrained internal geometry of a humanoid chassis complicates optimal battery pack integration, often forcing suboptimal compromises that can adversely affect the robot's centre of mass, dynamic balance, and structural integrity.

Thus, although LIBs are currently indispensable, they represent a significant performance bottleneck. Facilitating the transition from experimental platforms to reliable, commercially viable products requires coordinated and multifaceted innovation. This process demands simultaneous progress in electrochemical materials, cell and pack architecture, advanced thermal management strategies, and intelligent, predictive energy control algorithms. The following sections will provide a detailed analysis of how current battery limitations affect humanoid robot performance and outline the critical pathways for integrated technological advancement.

CHALLENGES IN POWERING HUMANOID ROBOTS

The design of battery systems for humanoid robots presents a uniquely complex engineering puzzle, in which the interdependent requirements of energy, power, and safety must be simultaneously optimized under severe mass, volume, and shape constraints, as illustrated in Figure 1.

The foremost challenge is achieving sufficient gravimetric and volumetric energy density to enable extended operational periods without incurring prohibitive penalties in size or weight. Given the need for a natural mass distribution and dynamic agility, the battery pack for a ~70 kg humanoid robot is typically constrained to 5–8 kg.[7] State-of-the-art commercial LIBs offer an energy density of approximately 250–300 Wh/kg. However, the practical energy density at the system level is significantly lower. This reduction results from the inclusion of critical pack-level components, including the

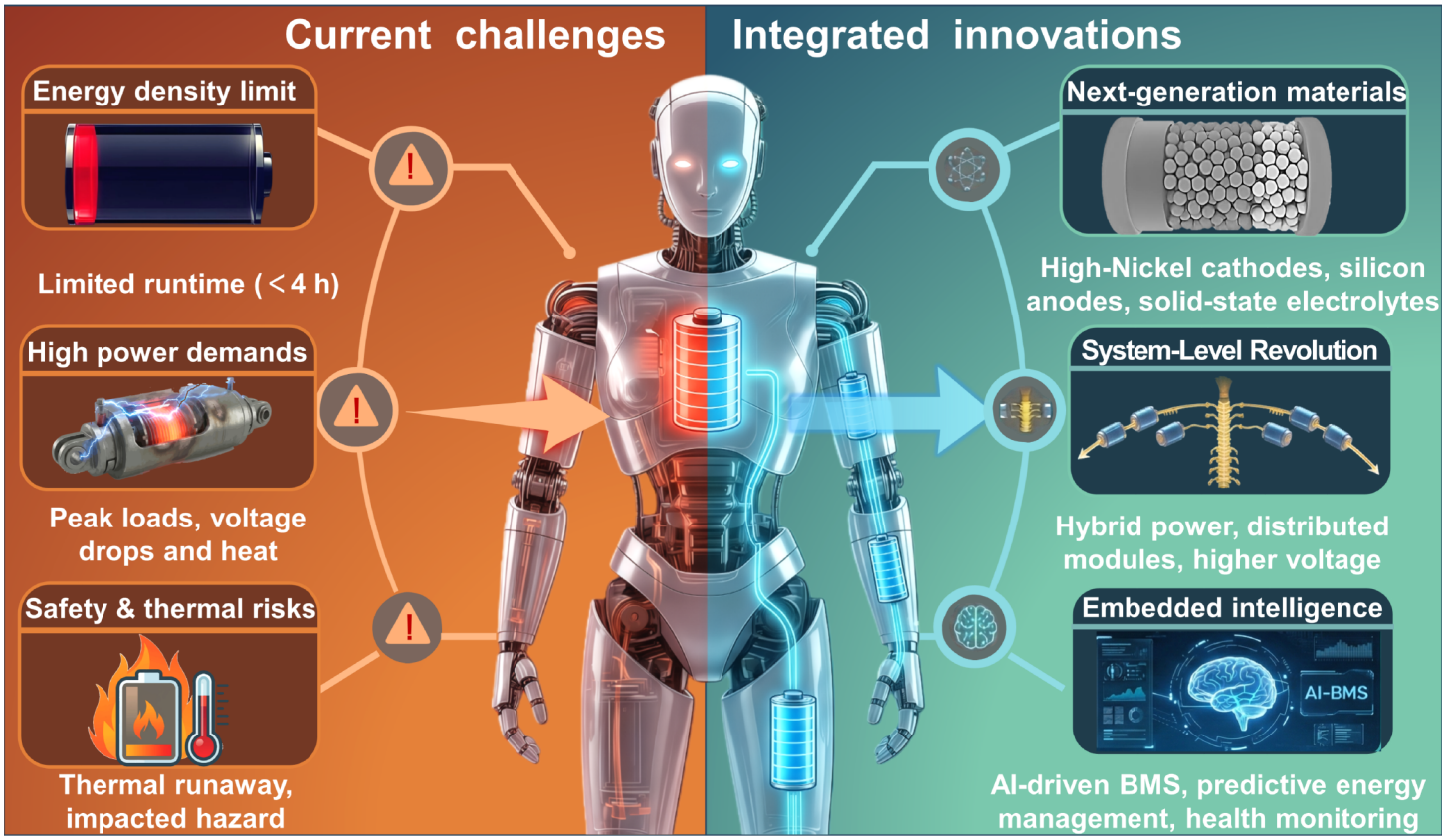

Figure 1. Current challenges and integrated innovations for battery techniques in humanoid robots

battery management system, wiring, structural housing, and thermal management hardware. As a result, the total energy capacity often limits operation to only 2–4 hours of mixed activity.[8] Achieving longer operational times requires at least 350 Wh/kg, making improvements in energy density a critical obstacle.

Humanoid robots also require exceptionally high power density. Dynamic actions such as walking, lifting, jumping, and balance recovery necessitate bursts of high electrical current, with discharge rates (C-rate) frequently exceeding 3 C to 5 C and even higher peak demands.These conditions place substantial stress on batteries, leading to undesirable voltage drops that can impair motor performance and control stability. Furthermore, the pursuit of high energy density often involves electrode designs and material choices that can intrinsically limit power capability, creating a fundamental trade-off. The battery must therefore be engineered to consistently meet these peak power demands with minimal voltage deviation and degradation, a requirement that challenges conventional cell design paradigms.

The operational-voltage platform itself imposes a limitation. Most current humanoid systems operate within a 48 V to 58 V range, a standard borrowed from industrial and mild-hybrid automotive applications. While offering some safety and component availability advantages, this voltage level requires high currents to deliver the multi-kilowatt power required for intense activity, leading to substantial resistive (I^2R) losses, increased cabling weight, and increased heat generation. Transitioning to higher-voltage platforms, such as 400 V or above in modern EVs, proportionally reduces current for a given power level. This approach improves drivetrain efficiency, decreases thermal load, and enables more powerful and sustained actuator output. This transition, however, requires a complete re-evaluation of motor drives, power electronics, and safety isolation systems within the robotic platform.

Finally, effective thermal management and safety are critical and non-negotiable design imperatives. The high specific power output within a confined space results in concentrated heat generation. Consequently, inadequate dissipation accelerates cell aging and reduces capacity. Furthermore, in extreme scenarios, it can induce thermal runaway, a catastrophic failure that is completely unacceptable for robots working closely with people. Humanoid robots operate in diverse environments, requiring batteries that operate reliably over a temperature range of −40 °C to 60 °C.[9] The packs must also be mechanically robust to withstand shocks, vibrations, and potential impacts inherent in mobile operation. Therefore, battery system design should integrate advanced thermal management strategies, such as embedded micro-channel cooling and phase-change materials, along with robust mechanical protection. while the Battery Management System (BMS) must enforce strict operational limits and provide robust fault detection and containment.

PATHWAYS FORWARD: INTEGRATED INNOVATION

Given these multifaceted challenges, it is essential to explore new directions and innovative approaches to effectively address limitations and advance the development of humanoid robots. Addressing these complex challenges necessitates a comprehensive strategy that extends beyond incremental technological advancements. Achieving success depends on progress in next-generation materials, innovative system architectures, and integrated intelligence, as shown in Figure 1.

Material and cell innovation

The quest for higher energy density is driving intensive research into novel electrochemical couples. Industry leaders are targeting cell-level energy densities of 350-500 Wh/kg in the near to medium term. Promising cathode developments include the progressive nickel-rich layered oxides (NCM/NCA) and the stabilization of lithium- and manganese-rich (LMR) cathodes. These innovations offer higher specific capacities. On the anode side, silicon-dominant anodes with silicon content exceeding 30 wt% provide a dramatic increase in theoretical capacity compared to conventional graphite. However, they face challenges related to volume expansion and cycle life. Solid-state batteries (SSBs) represent a paradigm-shifting direction. They replace flammable liquid electrolytes with solid ion conductors, potentially enhancing safety while enabling the use of lithium metal anodes for ultra-high energy density.[8] Several companies are actively developing semi-solid and solid-state battery prototypes specifically targeting the high-energy, high-reliability needs of robotic applications. Parallel research into lithium-sulfur and other beyond-lithium-ion chemistries also holds long-term promise.

Architectural and system-level revolution

Beyond the cell, a radical rethinking of power system architecture is essential. The conventional model of a single, monolithic battery block is giving way to distributed, hybrid power architectures.[10] Such systems typically utilize a primary high-energy-density backbone battery, positioned in the torso or pelvis, to provide baseline power for computation and general mobility. This configuration is supplemented by localized, high-power-density energy buffers, such as advanced LIBs optimized for power or ultracapacitors, which are strategically positioned near major joint actuators, including the hips, knees, and shoulders. This decentralization minimizes power transmission losses and cable mass, reduces peak current draw from the main pack, and improves thermal management by distributing heat sources. It also allows for more optimal mass distribution, enhancing the robot's dynamic agility and balance. Complementing this trend is the development of custom, form-factor-specific battery packs. By using flexible circuit boards and cell-to-pack integration techniques, batteries can be designed to conform to the irregular, non-rectangular voids within a humanoid's skeletal structure, thereby maximizing volumetric energy density. This demands close co-design between roboticists and battery engineers from the earliest stages of platform development.

At the same time, engineers are advancing toward higher voltage platforms beyond the usual 48 to 58 V range. Operating at higher voltages reduces the electrical current required for equivalent power. This change minimizes resistive losses and heat generation. These enhancements increase actuator output capacity. Systems can achieve more powerful movements without added thermal stress.

Intelligent management and connectivity

The role of the BMS is evolving from a passive protector into an intelligent, predictive core of the robot's energy strategy. Next-generation BMS will leverage artificial intelligence and machine learning to become cognitive energy managers. By integrating data from the robot's task scheduler, motion planner, and real-time sensor suite, the BMS can forecast energy demands for upcoming actions. It can perform proactive load balancing between central and distributed storage elements, optimize charging strategies, and employ advanced diagnostic techniques, such as electrochemical impedance spectroscopy, for precise, in-situ monitoring of state-of-health and state-of-power. Such an intelligent BMS can precondition the battery thermally and electrically for anticipated high-load tasks, provide early warnings for required maintenance, and implement sophisticated safety protocols tailored to specific operational contexts. This shift enables safer, more reliable, and application-aware energy utilization over thousands of charge-discharge cycles. Furthermore, developing industry standards and safety certification is essential for reliability and commercializing humanoid robots as they integrate into human environments.

CONCLUSIONS

The development of general-purpose humanoid robotics is fundamentally constrained by onboard energy systems. While advances in artificial intelligence, sensing, and actuation establish the potential capabilities, battery technology ultimately determines the operational endurance, mobility, and reliability. Addressing this challenge requires resolving a persistent trilemma among energy density, power capability, and safety within compact humanoid designs. Incremental improvements to existing battery technologies are insufficient. Instead, meaningful progress will depend on integrated advances in battery materials, power-system architectures, and intelligent control. Emerging battery technologies, such as solid-state and silicon-anode chemistries, offer promising pathways but must be evaluated in the context of system-level performance and integration. Additionally, hybrid power systems can enhance overall performance. Intelligent battery management systems must evolve into predictive energy management platforms to ensure efficiency, safety, and reliability. Ultimately, progress in humanoid robotics will rely on a co-design paradigm that tightly couples battery material, systems engineering, and embodied artificial intelligence.

REFERENCES

1. Cao L. (2025). Humanoid Robots and Humanoid AI: Review, Perspectives and Directions. *ACM Comput. Surv.* **58**:1–37. DOI:10.1145/3770574
2. Li W., Wu J., Yang G., et al. (2025). Humanoid robots: progress, challenges, and future research directions. *Sci. China Inf. Sci.* **68**:216201. DOI:10.1007/s11432-025-4532-0
3. Tong Y. C., Liu H. T. and Zhang Z. T. (2024). Advancements in Humanoid Robots: A Comprehensive Review and Future Prospects. *IEEE-CAA J. Autom. Sin.* **11**:301–328. DOI:10.1109/Jas.2023.124140
4. Geng Y., Tang H., Ji W., et al. (2025). Mobile Energy Storage (MES): A Grid-Edge Technology for Power Redistribution and Resilience Enhancement. *Energy Use* **1**:100022. DOI:10.59717/ipj.energy-use.2025.100022
5. Ngoy K. R., Lukong V. T., Yoro K. O., et al. (2025). Lithium-ion batteries and the future of sustainable energy: A comprehensive review. *Renew. Sust. Energ. Rev.* **223**:115971. DOI:10.1016/j.rser.2025.115971
6. Deng J., Yu X., Pang D., et al. (2025). Cutting-edge gas sensor design for monitoring thermal runaway in lithium-ion batteries: A critical review. *J. Energy Chem.* **109**:769–785. DOI:10.1016/j.jechem.2025.06.025
7. Sheng Q., Zhou Z., Li J., et al. (2025). A Comprehensive Review of Humanoid Robots. *SmartBot* **1**:e12008. DOI:10.1002/smb2.12008
8. Khan A., Al Rashid H., Roy P. K., et al. (2025). Challenges and the Way to Improve Lithium-Ion Battery Technology for Next-Generation Energy Storage. *Energy Environ. Mater.* **8**:e70088. DOI:10.1002/eem2.70088
9. Li C., Li Y., Su T., et al. (2025). Wide-Temperature, High-Voltage, Flame-Retardant Electrolyte for 4.8V Li||NCM94 Batteries. *Angew. Chem. Int. Ed.* **64**:e202509744. DOI:10.1002/anie.202509744
10. Mukherjee R., Ganguly P. and Dahiya R. (2023). Bioinspired Distributed Energy in Robotics and Enabling Technologies. *Adv. Intell. Syst.* **5**:2100036. DOI:10.1002/aisy.202100036

FUNDING AND ACKNOWLEDGMENTS

This research was funded by the National Natural Science Foundation of China (Nos. 52325801, 52578136, 52402052). Academic Papers of the 28th Annual Meeting of the China Association for Science and Technology.

DECLARATION OF INTERESTS

The authors declare no competing interests.