CONNECTING THE FUTURE

Engineering Connectivity for Robotic Upper Body Systems

Design Approaches for Humanoid Robots with Complex Movement Including Bending, Flexing, and Hand Gripping

VOLUME 2:
Upper Body, Arm & Hand Systems

HIROSE ELECTRIC AMERICAS

Connector Solutions for Today's Challenges — & Tomorrow's Needs

Table of Contents

HIROSE ELECTRIC AMERICAS

CONNECTING THE FUTURE

Designing Connectivity for
Humanoid Robotic Upper Body Systems

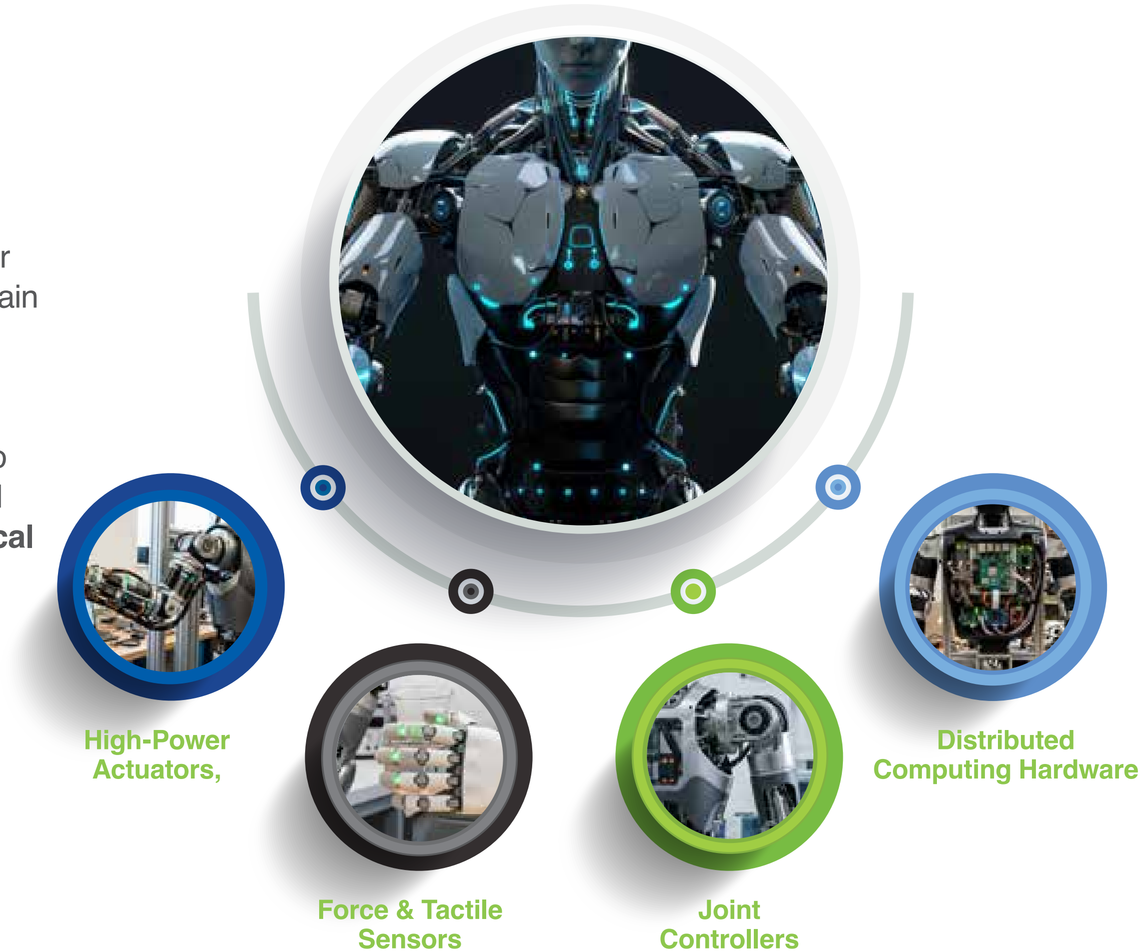
Humanoid robots are designed to operate in dynamic, unstructured environments—but it is the upper body that enables meaningful physical interaction. **Shoulders, arms, and hands must coordinate precise motion, apply controlled force, and respond to real-time feedback,** all within compact, articulated structures.

These systems integrate **high-power actuators, force and tactile sensors, joint controllers, and distributed computing hardware.** Unlike stationary or fixed-axis robotics, upper body assemblies must maintain reliable electrical performance while continuously moving, flexing, & adapting to external forces.

This shifts the design problem from system definition to maintaining performance under continuous motion and load. **Power delivery, signal integrity, and mechanical reliability** must be maintained across multiple joints and embedded control points—often within tightly constrained space and weight limits.

> **ENGINEERING INSIGHT**
> **Electrical reliability in upper body systems is driven as much by mechanical motion as by signal performance.**

Core Subsystems in a Humanoid Robotic Upper Body



Connector selection becomes a system-level design decision—not a late-stage component choice. Addressing these requirements early in the design cycle is essential to achieving reliable, manufacturable systems.

From Research Labs to Industrial Pilots

As humanoid robotics moves toward deployment, engineering focus is shifting from demonstrating capability to **validating long-term performance under real operating conditions.**

Unlike perception-focused systems, upper body assemblies must handle objects, apply force, and **adapt to unpredictable conditions** in real time.

This introduces a distinct set of engineering requirements. **Upper body systems must balance strength, precision, and responsiveness** while operating within strict constraints for weight, power distribution, and thermal management.

Key areas of focus include:

- **Precise force control for manipulation and handling**
- **Coordinated multi-joint motion across shoulders, elbows, and wrists**
- **Integration of tactile and force sensing for feedback-driven interaction**
- **Distributed control architectures that reduce latency and wiring complexity**

As these systems evolve, the challenge is no longer enabling motion—**but integrating motion, sensing, and control within compact, articulated structures that must perform reliably under continuous use.**

“Engineering Insight

Humanoid robotics is fundamentally a systems engineering problem—success depends on how effectively sensing, actuation, control, and communication are integrated across the entire system.”

Source: McKinsey & Company, recent interview on human–machine collaboration

HRS

Market Insight

Industry analysts estimate the global humanoid robotics market will grow from:

$2.92 billion in 2025

$15.26 billion by 2030

Potentially $243.4 billion by 2035

Sources: MarketsandMarkets; Research and Markets, March 2026

Market Drivers:

Several industry forces are accelerating the shift from research to deployment:

- Labor market pressure driving automation demand
- Advances in AI-enabled dexterity and perception
- Ongoing efforts to reduce system cost and complexity
- Increased venture and strategic investment in robotics platforms

As these trends converge, organizations are moving beyond pilot programs and investing in **scalable robotic solutions that deliver measurable business value.** Advances in **AI, sensor technology, computing power, and connectivity** are enabling robots to perform more complex tasks with greater precision and adaptability. As a result, manufacturers and logistics providers are **accelerating automation investments to improve productivity,** address labor shortages, and achieve faster return on investment.

From System Barriers to Design Constraints

As outlined in Volume 1, humanoid robotics faces four primary barriers to scale: safety, uptime, dexterity, and cost.

In upper body systems, these barriers translate directly into design constraints tied to motion, system integration, and manufacturability.

Upper Body Design Constraints

1

➜ Reliability Under Continuous Motion & Load

Upper body systems operate under constant articulation, vibration, and mechanical stress—particularly across shoulders, elbows, and wrists. Maintaining consistent electrical performance over millions of motion cycles is a key requirement for long-term deployment.

2

➜ System Integration Across Distributed, High-Density Assemblies

Upper body architectures distribute sensing, actuation, and control across multiple joints and embedded nodes. Real-time interaction requires continuous data exchange between depth cameras, IMUs, force-torque sensors, and tactile arrays, processed across distributed control systems. This increases the number of interconnect points while reducing available space for routing and integration.

3

➜ Manufacturability & Serviceability at Scale

As upper body systems increase in complexity, wiring, assembly, and maintenance become significant cost drivers. System design must account for how components are integrated, accessed, and serviced over time.

Connector Considerations:

Connectors must maintain stable contact integrity under continuous flex, vibration, and cyclic loading.

Connector Considerations:

High-speed, high-density connectors must support real-time data transfer between distributed subsystems while maintaining signal integrity and minimizing routing complexity.

Connector Considerations:

Connector solutions that simplify harness design, enable modular connections, and reduce mating complexity improve assembly efficiency and long-term serviceability.

These constraints directly influence how upper body systems are architected and how interconnect solutions must be selected.

THE HUMANOID UPPER BODY
is a tightly coupled assembly of sensing, actuation, and control subsystems that must operate together in real time. Achieving reliable performance requires tight coordination between mechanical design and electrical integration.

Subsystem Integration in Upper Body Systems

Cable routing paths, connector placement, and harness geometry must be **co-designed with the mechanical structure from the outset,** as available space is limited and continuously changes as joints move through their range of motion.

Within these closed-loop systems:

- Sensors Generate Perception Data
- Force-Torque Sensors Enable Motion Control
- Tactile Arrays Detect Contact, Pressure, & Slip
- Processors Interpret Sensor Feedback
- Control Systems Coordinate Motion & Interaction

All of these subsystems must exchange data in real time while arms move and hands manipulate objects. Maintaining reliable electrical connections across these continuously moving assemblies is therefore a fundamental system requirement—not just a component consideration.

Upper Body System Architecture:
A Hierarchical Systems Perspective

Understanding the electrical and mechanical architecture of a humanoid upper body requires thinking in terms of interconnected subsystems—from the central compute and power infrastructure in the chest to distributed control nodes and sensing systems throughout the arms and hands.

These systems must operate together in real time while the structure is continuously moving, loading, and changing geometry. As a result, connector selection and routing strategy are tightly coupled to mechanical design, motion paths, and overall system architecture.

Chest: Central Integration Hub

FUNCTION:

The chest acts as the central aggregation point for power, compute, and communication. It typically houses high-current power distribution, real-time control processors, and communication interfaces connecting to all upper body subsystems.

All power and data from the extremities route through the chest, making it the most heavily loaded zone in the harness.

DESIGN CONSIDERATIONS:

This region carries the highest concentration of power and data pathways. Harnesses from both arms converge here, creating dense routing zones with limited available space. At the same time, the chest must remain accessible for service while absorbing vibration and mechanical loads transmitted through the torso during motion and manipulation.

Thermal management and cable organization become critical, as poor routing or connector placement can restrict airflow, increase heat concentration, or complicate assembly and maintenance.

CONNECTOR IMPLICATIONS:

Connectors must support high pin counts, mixed power and signal transmission, and secure locking while maintaining reliability under vibration and repeated service access.

Upper Body System Architecture:
A Hierarchical Systems Perspective

Shoulders: High-Stress Routing Zones

FUNCTION:

The shoulder enables multi-axis motion—including flexion/extension, abduction/adduction, and internal/external rotation—with ranges approaching or exceeding human capability. It is the primary transition point between the fixed torso and moving arm.

DESIGN CONSIDERATIONS:

All cabling passing through the shoulder must accommodate continuous multi-axis articulation. This introduces combined bending, torsion, and compression forces that change dynamically with movement.

Routing paths cannot be static—they must account for the full motion envelope of the joint. Poorly managed routing can lead to localized stress points, cable fatigue, or interference with mechanical components. Maintaining consistent bend radius and strain relief across all positions of motion is a persistent challenge.

Standard cable routing approaches such as coiled tethers or flexible flat cables are often insufficient for the multi-axis rotational demands of the shoulder. Routing strategies must account for combined bending, torsion, and dynamic loading across the full range of motion, requiring carefully managed slack, strain relief, and controlled cable paths.

CONNECTOR IMPLICATIONS:

Connectors at shoulder transition points must maintain stable contact integrity under continuous cyclic loading while supporting routing strategies that minimize stress concentration at the interface.

Upper Body System Architecture: A Hierarchical Systems Perspective

Arms & Elbows: Distributed Control Intelligence

FUNCTION:

Humanoid arms distribute control intelligence across the limb rather than centralizing it in the chest. Shoulder, elbow, and wrist joints manage local motion, current control, & position feedback, enabling faster response to external inputs & improved manipulation stability.

DESIGN CONSIDERATIONS:

Each joint typically integrates embedded control electronics that process sensor feedback locally and communicate with higher-level systems over real-time communication buses (e.g., EtherCAT or similar deterministic protocols). This distributed architecture reduces latency and improves responsiveness, but significantly increases the number of interconnect points and embedded assemblies throughout the arm.

Cabling must support both power delivery and high-speed data communication while crossing multiple joint boundaries. As signals move between distributed nodes, maintaining synchronization and signal integrity becomes critical—particularly during coordinated, multi-axis motion.

Routing must also accommodate continuous articulation across the elbow and forearm. Repeated flexing and rotation introduce fatigue risks, requiring careful control of bend radius, strain relief, and cable path through the full range of motion.

CONNECTOR IMPLICATIONS:

Connectors must support high-density power and signal integration, enable reliable communication between distributed control nodes, and maintain performance under continuous motion and mechanical stress.

CONNECTOR IMPLICATIONS:
Connector solutions must support extreme miniaturization, high contact density, and reliable signal transmission while maintaining durability under repeated flexing and motion.

Upper Body System Architecture:
A Hierarchical Systems Perspective

Hands: High-Density Sensing and Actuation

FUNCTION:
The humanoid hand enables grasping, manipulation, and in-hand object control through multiple small joints operating in coordination. It combines actuation and sensing to replicate human-like dexterity.

DESIGN CONSIDERATIONS:
This is the most space-constrained region in the upper body. A five-fingered hand may incorporate 15–20 degrees of freedom, each requiring power and control signal routing within extremely limited space. Tactile arrays in the fingertips, force-torque sensing at the wrist, and additional proximity or optical sensors all increase conductor count within a very limited volume.

All of this must fit within a human-scale envelope for size and weight, placing strict limits on cable diameter, connector footprint, and routing paths. Tight bend radii, limited clearance, and interference with moving mechanical components further complicate integration.

The mechanical environment is also highly demanding. Finger joints experience continuous, high-cycle flexing—often reaching hundreds of millions of cycles over the system lifetime—placing significant stress on cable assemblies and connector interfaces.

Design Challenges:
Humanoid Robotic Upper Body Systems

Did You Know?

Distributed control and high-density sensing can drive 100+ interconnect points within a single humanoid upper body, making connector selection a key factor in routing, reliability, and long-term performance.

Building on the system architecture outlined in the previous section, these subsystems must operate together under continuous motion, high data throughput, and increasing interconnect density.

Under these conditions, connector limitations begin to emerge at the system level. Signal integrity, current capacity, and mechanical durability can directly influence sensing accuracy, actuator performance, and long-term reliability.

Key design challenges include:

1. High-speed signal integrity

Distributed sensing and control require continuous data exchange between sensors, embedded nodes, and central processors. As perception systems become more advanced, higher data rates must be maintained across densely routed interconnects and moving assemblies. Poor signal integrity can limit sensor resolution, increase latency, or reduce system responsiveness.

2. Miniaturization vs Current Capacity

High-torque actuators—particularly in the shoulder and elbow—require substantial current, while available space remains constrained. Interconnect solutions must balance compact size with the ability to carry continuous electrical load without introducing thermal constraints.

3. Flex Life & Fatigue

Connector interfaces in high-motion zones must maintain electrical performance under repeated bending and rotation. While cable construction—such as fine-stranded or rope-lay conductors and flexible insulation systems—supports dynamic motion, failures often occur at the connector interface where mechanical stress is concentrated.

Connector design must support controlled strain transition between cable and termination, preventing stress concentration at the contact or backshell interface. Inadequate strain management can lead to contact instability, conductor fatigue at the termination point, and premature failure under cyclic motion.

4. Vibration & mechanical stability

Connector performance must be maintained under continuous vibration, shock, and dynamic loading. Small relative movement at the contact interface (micro-motion) can reduce contact stability and lead to intermittent electrical behavior.

Over time, this can cause fretting wear at the contact surface, increasing resistance and degrading performance. Connector design must ensure stable contact engagement, secure retention, & resistance to loosening under cyclic mechanical stress.

“

DESIGN RULE:

Connector performance in humanoid systems must be validated under dynamic conditions. Positive locking, contact stability, and normal force should be verified against real vibration and motion profiles—not assumed from static retention data.

”

Connector Solutions for
Humanoid Robotic Upper Body Systems

Different regions of the upper body introduce fundamentally different electrical and mechanical requirements. Connector strategies must account for motion profile, routing density, power demand, signal integrity, and long-term mechanical reliability across continuously moving assemblies.

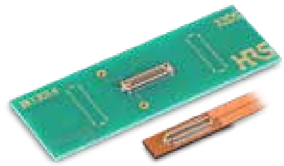
→ Compact Integration and Interconnect Density

Upper body systems require a **high number of interconnects within limited space,** particularly in distributed control nodes and embedded joint electronics. As sensing and actuation increase, connector density becomes a limiting factor in system layout & routing. Connector solutions must support **high contact density, compact form factors, & the integration of both power and signal** within constrained mechanical envelopes.

→ Hybrid Power and Signal Connectors

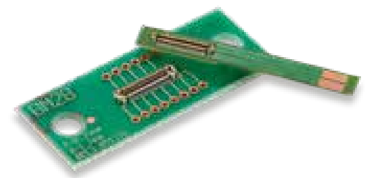
Distributed control architectures often require both power and signal connections at the same location. Using separate connectors increases **routing complexity, connector count, and assembly effort.**

Hybrid connectors consolidate these connections into a single interface, reducing harness complexity and simplifying integration.



BK13 Series

Micro board-to-board hybrid connector supporting combined power (up to 5 A) and high-speed signal transmission, reducing interconnect count while maintaining alignment tolerance and durability under motion



BM28 Series

Micro board-to-board hybrid connector supporting combined power (up to 5 A) and high-speed signal transmission, reducing interconnect count while maintaining alignment tolerance and durability under motion

→ Low-Profile, Reduced Pitch Connectors

As interconnect density increases, available space for connectors becomes limited—particularly in hands, wrists, and embedded joint electronics. **Smaller pitch and lower profile connectors enable more connections** within a given area without increasing system size. These connectors support higher conductor density while maintaining electrical performance and mechanical reliability in compact assemblies.

BK35 Series

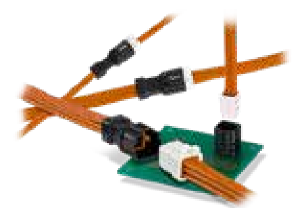
Ultra-low-profile hybrid connector with 0.6mm stacking height, supporting power and high-frequency signal transmission in space-constrained layouts

KW30 Series

Compact wire-to-board connector supporting up to 3A, designed for stable power delivery in dense, vibration-prone areas

DF61Y Series

Low-profile wire-to-board connector enabling efficient routing in tight mechanical spaces and improving layout flexibility



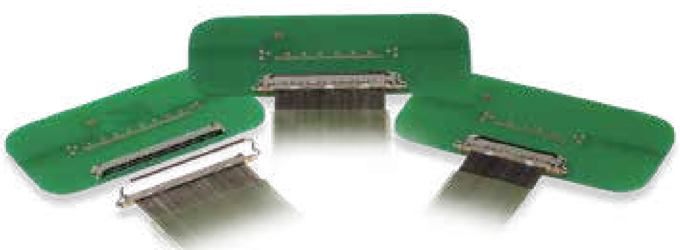
DF62W Series

Compact sealed connector providing environmental protection and reliable performance in small, exposed areasmotion

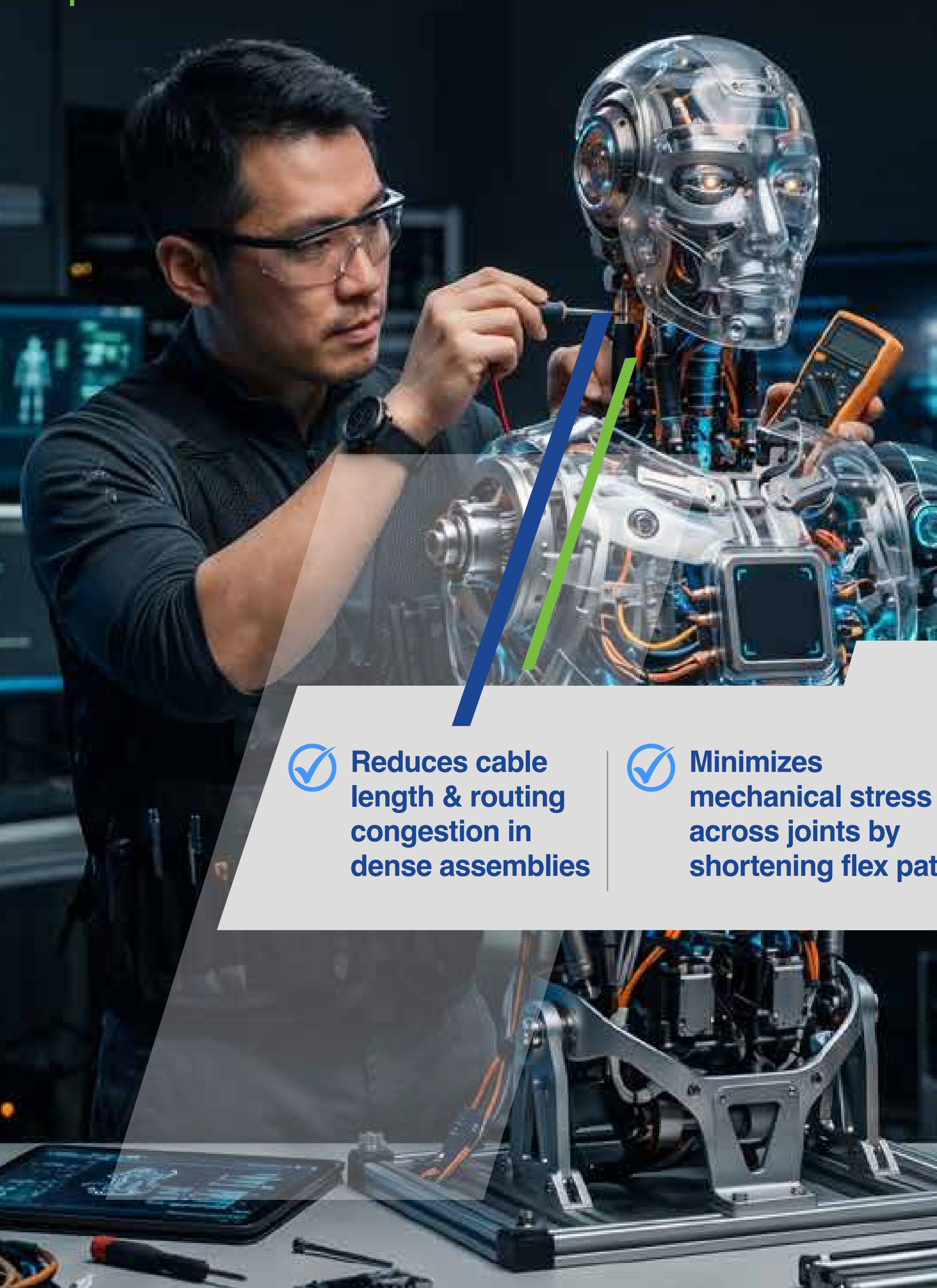
Upper body systems rely on real-time data exchange between sensors, control nodes, and processing systems.

As perception capabilities expand, maintaining signal integrity under motion becomes a key design requirement.

Connector solutions must support **high-speed data transmission while minimizing signal degradation and maintaining stable performance** in electrically and mechanically active environments.



DF81 SERIES
Micro-coaxial connector designed for high-speed signal transmission in compact, articulated sections, maintaining signal integrity under motion and dense routing conditions

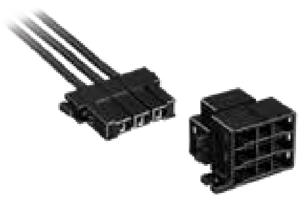


Branch & Distribution Connectors

Branch and distribution connectors enable multiple connections from a primary harness, allowing power and signals to be distributed across the system through localized connection points.

This approach addresses several key design challenges:

- Reduces cable length & routing congestion in dense assemblies
- Minimizes mechanical stress across joints by shortening flex paths
- Improves scalability as additional subsystems are introduced
- Supports modular design and faster system iteration
- Simplifies assembly & serviceability



DF22B Series:

High-current branch adapter (up to 30 A) supporting efficient power distribution across multiple subsystems, reducing cable length and centralized routing complexity

DF51B Series:

Positive-lock branch connector enabling secure, vibration-resistant connections at localized distribution points, supporting reliable performance in motion-intensive environments

HIROSE ELECTRIC AMERICAS

Designing Reliable Humanoid Robotic Systems

CONNECTING THE FUTURE

As humanoid systems move toward **real-world deployment,** connectivity decisions become increasingly difficult to change later in the design process.

Connector selection influences not only signal performance, but also **mechanical reliability, routing feasibility, & long-term serviceability.** In compact, motion-intensive assemblies, these factors are tightly coupled—small design tradeoffs can introduce system-level constraints that are difficult to resolve once architectures are established.

Designing connectivity early, alongside system architecture, helps prevent avoidable redesign cycles, simplifies integration, and **improves long-term system reliability.** In humanoid systems, connector decisions don't just support the design**—they define what the system is capable of.**

Continue Exploring Humanoid Robotics

Watch the Webinar

Connector Selector Guide

Humanoid Robotics eBook Series View Series

Contact Us

SOURCES: MarketsandMarkets, Humanoid Robot Market – Global Forecast to 2030 — https://www.marketsandmarkets.com/Market-Reports/humanoid-robot-market-99567653.html
Research and Markets, Global Humanoid Robots Market Report, March 2026 — https://www.researchandmarkets.com/reports/6197133/global-humanoid-robots-market-report-2026