THE HUMANOID HARDWARE VALUE CHAIN

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Can the European Manufacturing Industry Capitalize on the Humanoid Momentum?

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Management summary

Structural change in the manufacturing industry, especially in the automotive sector, is accelerating the search for new growth opportunities. Humanoid robotics is gaining strategic relevance as a future market that closely aligns with established competencies in automation, mechatronics, and industrial manufacturing. Early engagement in the humanoid hardware value chain offers European manufacturers a tangible opportunity to capture value in this emerging field. Market projections indicate substantial growth potential. The global humanoid robotics market is expected to reach a volume of approximately USD 30 billion by 2030[1]. Long-term scenarios project a worldwide installed base of several hundred million humanoid robots by 2050[2]. These developments highlight the relevance of early engagement with the underlying value chain.

This whitepaper analyzes the role of hardware in the context of the industrialization of humanoid robots. Despite advances in artificial intelligence, the economic viability, reliability, and scalability of humanoid systems are largely determined by hardware components. At present, standardized hardware architectures are lacking, and key components such as actuators, gearboxes, batteries, and sensors only partially meet industrial requirements in terms of robustness, lifetime, and cost structure.

To quantify these challenges, the study combines a layered analysis of humanoid hardware architectures with a bottom-up cost model. The resulting cost scenarios, summarized in Figure 1, enable a structured comparison of low-, mid-, and high-cost humanoid configurations and illustrate how different hardware choices translate into overall system cost. The analysis highlights hardware components that dominate overall expenditure and represent key challenges for cost-efficient scaling, particularly for humanoid systems intended for continuous industrial operation.

For European manufacturers, this represents a concrete strategic opportunity. The capabilities required for humanoid hardware, including precision mechatronics, advanced manufacturing, and system integration, align closely with established strengths of European automotive suppliers and mechanical engineering companies. Capturing value

[1] Citigroup 2024; https://www.citifirst.com.hk/home/upload/citi_research/rsch_pdf_30297368.pdf
[2] P3 market model

in this emerging market will depend on a focused engagement in the development and industrialization of cost- and performance-relevant hardware components, combined with early and close collaboration with humanoid OEMs.

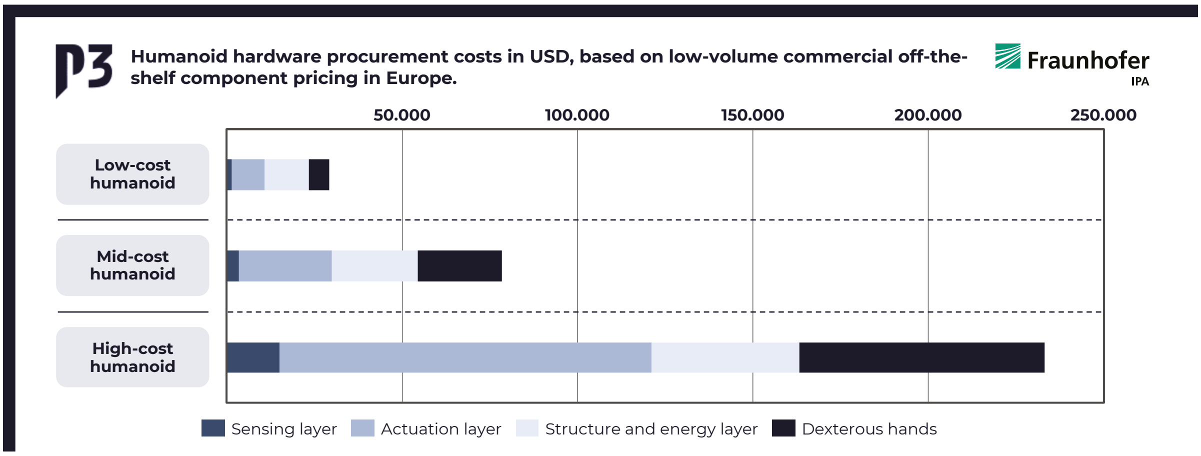

Figure 1: *Estimated humanoid hardware cost in USD based on humanoid cost model. The cost assessment is based on low volume hardware procurement cost in 2026 and sourcing for the European market.*

1. Point of Departure

The manufacturing industry is undergoing a structural transformation. In particular, automotive manufacturers and their supplier networks are under pressure as rising energy costs, geopolitical tensions, and intense global competition reduce traditional value creation and employment volumes. Against this background, many industrial actors are seeking adjacent markets in which existing competencies in automation, mechatronics, precision manufacturing, and industrialization can be leveraged, both to compensate for declining volumes and to open up new growth opportunities.

In this context, humanoid robotics has gained strategic relevance. The objective of current development efforts is a universally deployable robot that can operate in environments designed for humans, be it in industrial or also private settings. Public demonstrations of humanoid robots illustrate progress in manipulation, locomotion, and interaction and have directed industrial attention toward this technology field. As a result, expectations have emerged that humanoid systems could, over time, contribute to the automation of labor-intensive tasks.

These expectations are supported by market projections. P3 market models estimate that the global humanoid robotics market could reach a volume of approximately USD 30 billion by 2030, corresponding to a compound annual growth rate (CAGR) of around ~60 percent. Long term scenarios, including those published by Citi Group, project a global installed base of up to 648 million humanoid robots by 2050.[3]

The current momentum in humanoid platform development is often attributed to advances in artificial intelligence. To an equal extent, however, it is enabled by hardware availability. According to market estimates, a substantial share of the value creation of humanoid systems is attributable to hardware components (see Figure 2). Sensors, electric drives, power electronics, and computing units originating from the automotive and automation sectors have accelerated development and enabled rapid prototyping as well as early industrial pilot applications. However, when these components are considered for continuous industrial operation in humanoid systems, limitations become apparent. These limitations arise not from insufficient quality of the components themselves, but

[3] Citigroup 2024; https://www.citifirst.com.hk/home/upload/citi_research/rsch_pdf_30297368.pdf

from differing design objectives and operating conditions. Performance, lifetime, energy efficiency, and operational safety in humanoid robots are largely determined by mechanical and electromechanical components such as actuators, gearboxes, batteries, and structural elements, which must withstand highly dynamic loads, strict weight constraints, and long duty cycles.

Against this background, the full realization of a universally deployable humanoid robot remains a long-term objective. Current systems are not capable of providing unrestricted autonomy across heterogeneous industrial environments. This is primarily due to the immense training effort required for robots and the lack of data sets for this purpose. Industrial adoption of humanoid robotics is therefore expected to begin with specialized systems tailored to clearly defined tasks. Material transport, machine loading, and the grasping of complex objects are regarded as early application fields, as they combine structured processes, a high share of manual labor, and comparatively bounded perceptual and manipulation complexity.[4] Accordingly, robotic OEMs are working closely with automotive manufacturers to evaluate use cases, validate system performance, and utilize existing production environments.

As a result, the humanoid hardware value chain is becoming a focal point of industrialization. Experience from electric vehicle battery cell manufacturing shows that early scaling, cost pressure, and industrial maturity strongly influence regional value creation. While Europe has been only partially successful in large scale battery cell production, humanoid robotics relies on high value mechatronic components, precision manufacturing, and system integration, areas in which European industry possesses established capabilities.

European automotive suppliers, machinery manufacturers and automation specialists have experience in high precision drive systems, lightweight design, advanced manufacturing processes, and industrial quality management. These capabilities provide a basis for participation in the emerging humanoid hardware value chain. However, this requires a clear understanding of maturity levels, cost drivers, and scaling risks across the humanoid hardware stack.

In response to these developments, Fraunhofer Institute for Manufacturing Engineering and Automation IPA and the P3 Group have conducted an analysis of the humanoid hardware value chain. Fraunhofer IPA is one of Europe's leading institutes for industrial

[4] Fraunhofer IPA 2025; https://www.ipa.fraunhofer.de/de/Publikationen/studien/humanoide-roboter.html

robotics, automation, and manufacturing research, with long standing experience in transferring robotics technologies into industrial practice. The institute has a strong track record of robotics related spin-offs and is actively involved in the Innovation Park Artificial Intelligence (IPAI), including research on humanoid manipulation and robotic hands.

Founded in 1996 as a spin-off from the Fraunhofer Institute for Production Technology (IPT), the P3 Group is a leading consultancy and software company deeply rooted in the automotive and manufacturing industry. Their portfolio covers a broad range of services, including technology studies, market and business intelligence, technology enablement, and software development.

This joint whitepaper aims to examine humanoid hardware architectures, identify critical bottleneck components and develop a bottom-up cost model to assess economic viability and industrial scaling potential. Following the introduction, Section 1 defines humanoid robots and outlines current target markets and industrial developments. Section 2 analyzes humanoid hardware architectures and assesses the maturity of key components across sensing, actuation, and structural and energy layers. Section 3 examines critical hardware components in detail. Section 4 presents a bottom-up hardware cost model. Section 5 discusses strategic implications and opportunities for European manufacturing.

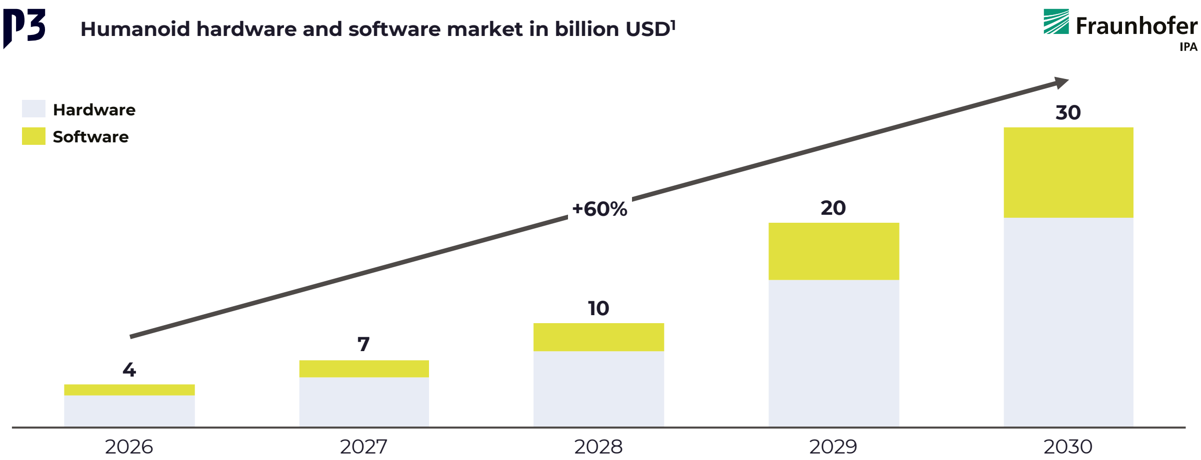

Figure 2: *Global humanoid market split by hardware and software value[5]. 1) Based on P3 market model.*

[5] P3 market model (bull case)

1.1. Definition Humanoid Robot

Humanoid robots represent a fundamental shift in automation. Unlike traditional industrial robots that are typically stationery and programmed for specific tasks, humanoid systems are designed to combine human-like mobility, dexterity, and adaptability. They are universally applicable mobile machines designed to resemble the human body and developed for work in environments intended for humans. They have various sensors to detect their surroundings and legs or a mobile platform for locomotion. They are part of a humanoid system that includes safety measures, system components like charging infrastructure and specific end effectors, in case the humanoid robot is not equipped with hands. Compared to conventional industrial robots with up to seven axes, humanoid robots can have more than 40 individually actuated axes, which highlights the potential for possible hardware suppliers[6].

1.2. Target Markets and Current Developments

The current landscape of humanoid robot development reveals a broad range of emerging applications, from industrial production and logistics to service and domestic environments. While some manufacturers focus on deploying humanoids in service tasks and household environments, others position their humanoid platforms as versatile automation solutions for factories and warehouses. Industrial settings are seen as an ideal entry point for deployment because their structured environments and repetitive workflows align with the current technological maturity of humanoid systems.

Global companies are advancing this field at high speed. Especially in the US and China a broad row of companies are working on the general purpose humanoid. **Figure AI** is among the technological frontrunners. Its **Figure 03** model targets household applications, while **Figure 02** is already operating at BMW's Spartanburg plant, performing machine tending tasks. In another internal pilot project, Figure showcases humanoid robots executing repetitive operations such as gripping, scanning, and sorting parcels on a conveyor. **Agility Robotics** focuses on warehouse and order-picking operations with Digit, tested with partners including Amazon and GXO. **Apptronik's Apollo**, currently tested in collaboration with Mercedes-Benz, is used for material handling, picking, and assembly and is operated under teleoperation to collect process data for future autonomous use.

[6] Fraunhofer IPA 2025; https://www.ipa.fraunhofer.de/de/referenzprojekte/kmumanoid.html

Tesla integrates **Optimus** directly into its production environment, where it performs sorting and visual inspection tasks and is envisioned as a scalable production workforce. **Boston Dynamics** presented the newest version of **Atlas** at CES 2026 as the most sophisticated humanoid to date. In Europe, **Neura Robotics** promotes its **4NE-1** as a multi-purpose humanoid for industry, service, and research, while **Hexagon's AEON** is designed for machine tending, inspection, and process data acquisition. The UK-based **Humanoid** follows a logistics-focused concept with its **HMND 01**, capable of operating within existing infrastructure. Chinese companies such as **Ubtech Robotics, Unitree and Xiaomi** are also accelerating industrial use cases for humanoid systems to address skilled labor shortages in manufacturing and logistics. Even though the names of Chinese developers are relatively unknown in the West, the sheer number of developers of more than 100 in China demonstrates the importance of humanoid robot development in Asia.[7] As the number of manufacturers increases steadily, only a selected subset of humanoid manufacturers in shown in Figure 3.

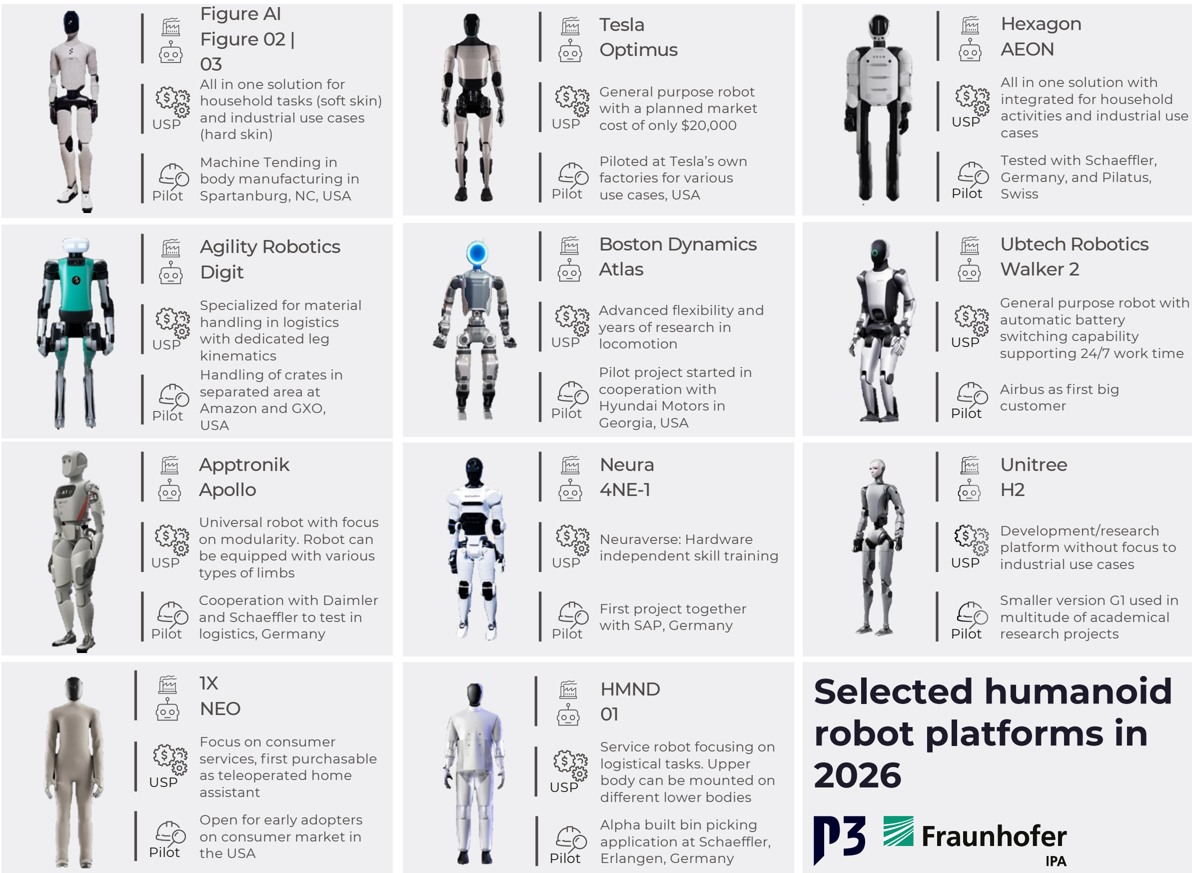

Figure 3: *Summary of the most promising humanoid robots for industrial use cases with information about their unique selling point ("USP") and current pilot projects (as of 02.26). Source: P3/Fraunhofer IPA; pictures taken from the companies' websites.*

[7] VDI 2026; https://www.vdi-nachrichten.com/technik/automation/roboter-2026-china-macht-tempo-und-die-usa-zeigen-deutsche-tugenden/

2. Hardware Maturity and Architecture for Humanoid Robots

Current humanoid robot platforms exhibit fundamentally different hardware architectures, as no dominant reference architecture has yet emerged. Existing designs reflect alternative tradeoffs between performance, durability, energy efficiency, safety, and cost across key architectural dimensions, including actuation concepts, sensing technologies, structural layouts, and energy systems. This architectural heterogeneity reflects the early stage of industrialization and represents a key challenge for scalability and long-term industrial deployment.

To enable a systematic assessment of hardware maturity and cost drivers across these heterogeneous architectures, humanoid robot systems are structured into three functional layers:

- **The Sensing Layer**
- **The Actuation Layer**
- **The Structural and Energy Layer**

This layered structure does not represent an industry standard. Rather, it serves as an analytical framework to consistently assess technological maturity, cost structure, and remaining engineering challenges across the humanoid hardware stack. Based on this layered architecture, the following sections introduce the main hardware building blocks of each layer and assess their maturity, cost structure, and key limitations.

Sensing Layer

The sensing layer forms the perceptual foundation of a humanoid robot. It enables environment perception, state estimation, and physical interaction and is therefore essential for locomotion, manipulation, and safe operation in human-centered environments. As illustrated in Figure 4, the sensing layer comprises a wide range of sensor modalities distributed across the humanoid body, including vision and depth sensors, tactile and force sensors, inertial sensors, and environmental sensors. Joint-internal sensing elements such as position encoders and joint torque sensors are assigned to the actuation layer in this analysis, as they primarily support closed-loop control within individual joints rather than environment perception.

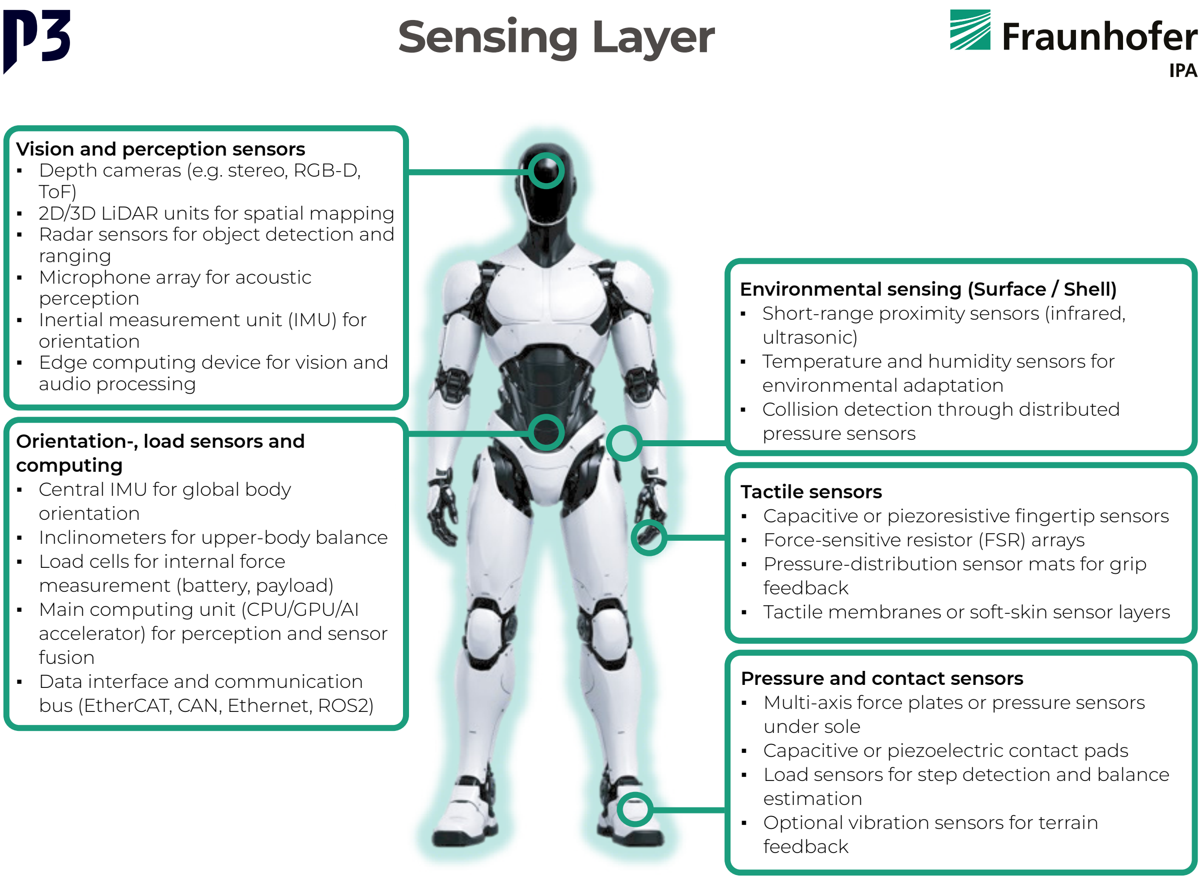

Figure 4: *Most relevant parts of the sensing layer.*[8]

Within this broad sensing stack, individual sensor technologies differ substantially in their relevance for humanoid performance, system cost, and industrial maturity. For the purpose of hardware assessment, four sensing hardware categories have been identified as particularly decisive for humanoid operation and scalability: Depth cameras, LiDAR systems, tactile and force sensors, and edge computing units.

While vision sensors and LiDAR benefit from high technical maturity due to their widespread use in automotive and autonomous systems, other components address fundamentally different challenges. In particular, tactile and force sensors remain a key bottleneck, as current solutions often lack the robustness and durability required for continuous industrial operation. Table 1 summarizes the technical maturity, cost level, and key challenges of these sensing components in the context of humanoid systems.

[8] Picture generated by AI (OpenAI)

Table 1: *Overview of maturity, costs, and challenges of critical sensing hardware. Cost: low-cost ($), mid-cost ($$), high-cost ($$$), very-high-cost ($$$$). 1) Technical maturity derived from technology readiness level (TLR) for humanoid operation. Technical maturity: low-maturity (1/4), mid-maturity (1/2), high-maturity (3/4), fully mature (1).*

Sensing Layer Hardware

Hardware	Technical maturity[1]	Cost	Challenges
Depth cameras	◕	**$$**	• Limited range • Coverage
LiDAR	◕	**$$**	• Processing power • Motion distortion
Tactile/Force sensors	◔	**$$$**	• Durability • Cost • Functionality
Edge SoC	◕	**$$$**	• Cost • Energy consumption

Actuation Layer

The actuation layer converts electrical energy into controlled mechanical motion and force and therefore determines the mobility, manipulation capability, and dynamic performance of a humanoid robot. To achieve human-like ranges of motion and force profiles, current humanoid platforms typically employ several dozen actuators distributed across the body. Accordingly, joint-internal sensing elements such as position encoders and joint torque sensors are considered integral components of the actuation system, as they primarily enable closed-loop control of individual joints. The functional composition of the actuation layer within a humanoid system is illustrated in Figure 5.

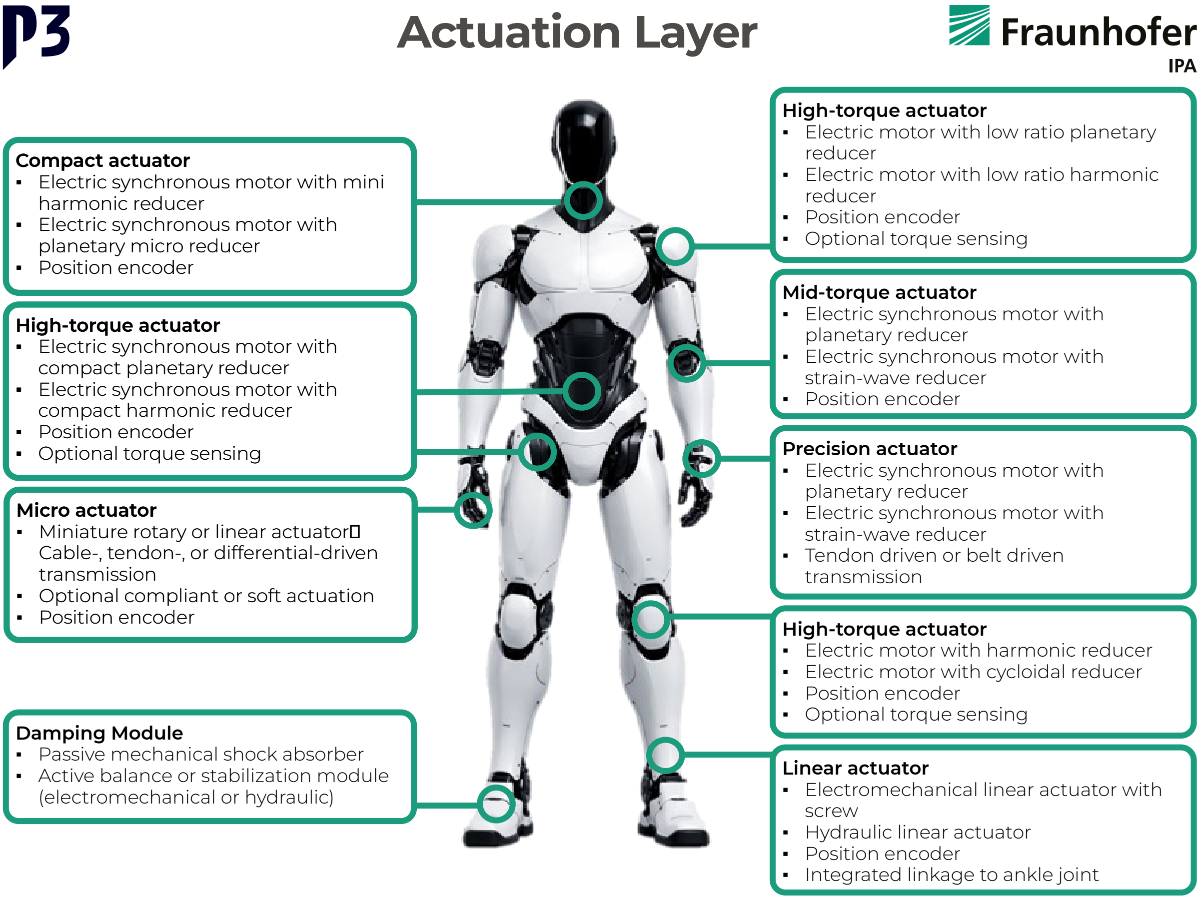

Figure 5: *Most relevant parts of the actuation layer.*[9]

Actuation concepts within humanoid robots span a wide range of trade-offs between precision, torque, complexity, and cost. Direct drive electric motors, for example, enable high precision movements without backlash, feature low mechanical complexity, and therefore require less maintenance. Nonetheless, direct-drive actuation is subject to certain limitations that restrict its applicability in scenarios demanding high torque output. Many humanoid and robotic applications exceed the practical torque range of direct drive systems or require cost-driven compromises.

Beyond joint actuation, the actuation hardware of the humanoid hand represents one of the most demanding subsystems within humanoid platforms. Object manipulation is a core capability for most envisioned use cases, making dexterous hands a critical design element. At the same time, their mechanical and control complexity introduces significant trade-offs between dexterity, robustness, and cost.

In-house humanoid testing has revealed that current typical bipedal humanoid actuation systems suffer significantly from wear and tear, inefficient energy use, heat accumulation

[9] Picture generated by AI (OpenAI)

and insufficient dexterity. Mechanical degradation in particular leads to a notable loss in precision and dexterity, while inefficient actuation systems and high weight further exacerbate energy consumption. Precision bearings within joints and transmission stages further contribute to lifetime limitations, efficiency losses, and overall system cost, as they are required in large numbers across the humanoid body. Alternative actuation concepts, such as hydraulic or pneumatic systems, are also explored in humanoid robotics, but currently remain limited to niche applications.

For the purpose of hardware assessment, four actuation hardware categories have been identified as particularly critical for humanoid operation and industrial scalability: electric motors, reducers, screws and specialized dexterous hand actuation systems. These components dominate system cost, mechanical reliability, and long-term performance and are therefore decisive for the feasibility of continuous industrial deployment. Table 2 summarizes the technical maturity, cost level, and key engineering challenges of the selected actuation hardware components in the context of humanoid operation.

Table 2: *Overview of maturity, costs, and challenges of critical actuation hardware. Cost: low-cost ($), mid-cost ($$), high-cost ($$$), very-high-cost ($$$$). 1) Technical maturity derived from technology readiness level (TLR) for humanoid operation. Technical maturity: low-maturity (1/4), mid-maturity (1/2), high-maturity (3/4), fully mature (1).*

Actuation Layer Hardware

Hardware	Technical maturity[1]	Cost	Challenges
Electric motors	◕	$$$	• Thermal mgmt. & efficiency • Weight/torque • Cost, precision & durability
Reducers	◕	$$$	• Durability • Precision • Complexity & cost
Screws	◕	$$$	• Complexity & cost • Supply • Manufacturing complexity
Dexterous hands	◔	$$$$	• Complexity & cost • Dexterity • Durability

Beyond technical maturity, several critical actuation components have not yet been produced on an industrial scale. Furthermore, expansion is limited by the availability of specialized production equipment, such as high-precision grinding machines (Screws).

Structural and Energy Layer

The structural and energy layer of humanoid robots is shaped by competing requirements related to dexterity, robustness, weight, and operational endurance. Figure 6 provides an overview of the key structural components and energy-related subsystems that jointly determine mechanical integrity, safety, and runtime characteristics.

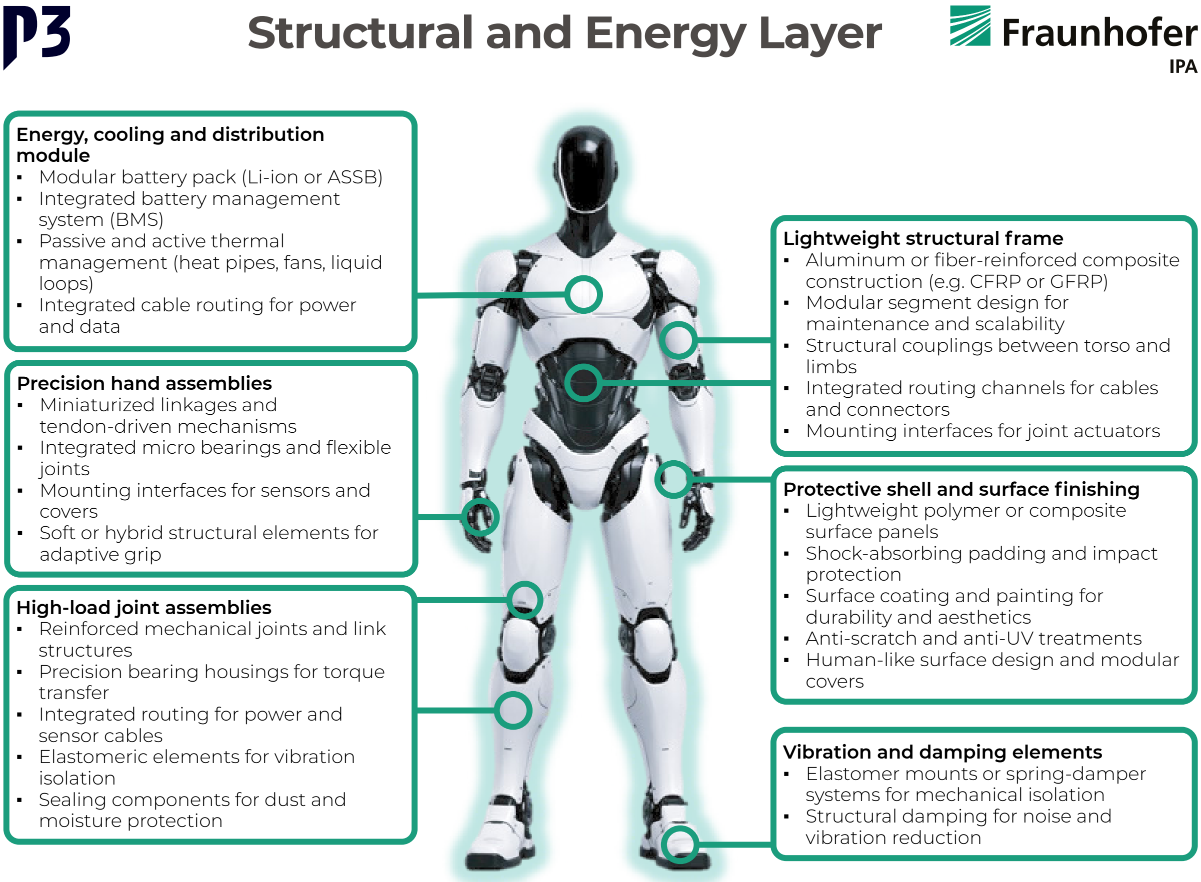

Figure 6: *Most relevant parts of the structural & energy layer.*[10]

In many current humanoid platforms, structural mass remains a relevant design consideration due to its direct impact on mobility, energy consumption, and collision safety. Unlike conventional industrial robots, humanoid systems combine highly dynamic motions, frequent load changes, and continuous interaction with their environment with strict constraints on weight, volume, and onboard energy storage. These conditions place stringent requirements on structural design, joint durability, and energy efficiency, thereby motivating the use of lightweight frames. Current humanoid systems typically employ

[10] Picture generated by AI (OpenAI)

aluminum or steel structures. Weight reduction can be achieved through advanced lightweight materials, including magnesium and titanium alloys, fiber-reinforced composites, and polymer-based structural and surface materials. Additional gains arise from optimized component geometries and manufacturing approaches such as additive manufacturing, which enable functional integration and structural optimization in low-volume or highly integrated components.

Beyond structural design, operational runtime is largely constrained by the energy storage system. While lightweight structures contribute to lower energy consumption, continuous autonomous operation over a full industrial work shift places high demands on battery systems. State-of-the-art lithium-ion batteries currently do not provide sufficient gravimetric and volumetric energy density to reliably support uninterrupted wireless operation across a broad range of industrial use cases without battery exchange or recharging. Next-generation battery technologies, including solid-state battery concepts such as lithium-sulfur systems, offer the potential for increased energy density and extended operational endurance in the medium to long term. These developments are particularly relevant for humanoid robots targeting extended autonomous operation in applications where battery swapping is impractical or economically unfavorable.

Table 3 summarizes the key structural and energy layer components identified in this study, highlighting their technical maturity, cost levels, and main challenges for humanoid robot operation.

Table 3: *Overview of maturity, costs, and challenges of critical structural and energy hardware. Cost: low-cost ($), mid-cost ($$), high-cost ($$$), very-high-cost ($$$$). 1) Technical maturity derived from technology readiness level (TLR) for humanoid operation. Technical maturity: low-maturity (1/4), mid-maturity (1/2), high-maturity (3/4), fully mature (1).*

Structural & Energy Layer Hardware

Hardware		Technical maturity[1]	Cost	Challenges
Battery		◕	**$$**	▪ Energy density
Skeleton		◑	**$$$**	▪ Weight ▪ Maturity of design ▪ Cost

3. Assessment of Critical Hardware Components

Following the system-level analysis of humanoid hardware architectures presented in Section 2, the subsequent sections provide a more detailed examination of selected hardware components. Given the breadth and heterogeneity of the humanoid hardware stack, not all components can be assessed in equal depth within the scope of this whitepaper. Therefore, P3 and Fraunhofer IPA conducted an in-depth assessment of a limited set of representative hardware components across the sensing, actuation, and energy layers. The analysis evaluates alternative technical concepts, component properties, limitations, maturity levels, key suppliers, and their suitability for integration into humanoid robot architectures under industrial operating conditions.

This whitepaper presents detailed assessment results for tactile sensors, electric motors, reducers, and batteries. These components were selected as illustrative examples, as they capture central technical trade-offs related to performance, durability, energy efficiency, and cost that recur across the humanoid hardware stack.

Table 4: *Hardware assessments presented in this whitepaper.*

The Humanoid Hardware Value Chain

Tactile sensors	**Electric motors**	**Reducers**	**Batteries**	LIDARs	Screws	Dexterous hands	Skeleton hardware	Cameras	Edge SoC
Presented in whitepaper				Not presented					

3.1. Sensing Layer - Tactile Sensors

While capacitive and piezoresistive tactile sensors are commonly used in consumer electronics, “next generation” tactile sensing technologies are being explored for future applications, such as robotics and healthcare. In the subsequent section, an examination of various tactile sensing technologies is explored. Optical and piezoelectric tactile sensors are not presented in this study.

Tactile sensing technologies (not exhaustive):

1. **Capacitive tactile sensors** detect changes in capacitance as a soft dielectric is compressed, offering thin, flexible integration into finger pads and curved surfaces. They provide high sensitivity to small forces but suffer from humidity, temperature drift and dielectric wear, which challenge long-term stability in humanoids.

2. **Piezoresistive tactile sensors** measure deformation through resistance changes and are robust, simple, and suitable for a wide force range in repeated fingertip contacts. Signal drift, hysteresis and poor resolution at low force make them less suitable for precise manipulation in humanoid robots.

3. **Gel-based tactile sensors** use a deformable gel to capture high-resolution contact geometry and micro-slip, enabling detailed perception for dexterous manipulation. Their bulk, higher power use, and exposed gel surfaces reduce practicality for rugged humanoid applications.

4. **Magnetic tactile sensors** detect changes in magnetic fields caused by deformation of an elastic structure with embedded magnets, typically measured using Hall or magnetoresistive sensors. Alternatively, they infer deformation through changes in electromagnetic induction.

Table 5 summarizes the key properties, applications, limitations, technical maturity for humanoid operation, and the key players of the explored tactile sensing technologies.

Table 5: *Summary of sensor hardware assessment. 1) Technical maturity derived from technology readiness level (TLR) for humanoid operation. Technical maturity: low-maturity (1/4), mid-maturity (1/2), high-maturity (3/4), fully mature (1).*

Sensing Hardware (not exhaustive)

Sensor type	Key properties	Application	Key limitations	Technical maturity[1]	Key players (Not exhaustive)
Capacitive	High sensitivity, flexible	Hands, skin	Drift, humidity, wear	◑	Tacterion (DE), Interlink Electronics (US), Nissha (JP)
Piezoresistive	Robust, low-cost	Hands, skin	Hysteresis, drift	◑	Interlink Electronics (US), Tekscan (US),
Gel-based	Very high resolution	Hands, skin	Bulky, wear, compute load	◔	GelSight Inc. (US), Shadow robot (UK)
Magnetic	High sensitivity, high robustness	Hands, skin	Design complexity, magnetic interference	◕	XELA Robotics (JP), Shadow robot (UK)

3.2. Actuation Layer - Electric motors

In humanoid robots, electric actuation is predominantly realized using permanent magnet synchronous motors due to their high torque density, efficiency, and suitability for compact joint architectures. The stringent spatial constraints distributed joint topology, and dynamic performance requirements of humanoid systems favor motor concepts that combine high power density with low inertia and flexible integration into the mechanical structure. Depending on joint requirements, electric motors can be operated as direct drive actuators or in combination with mechanical reducers (see section 3.3).

In industrial practice and technical literature, motors for robotic joints are commonly described using a combination of electromagnetic, geometric, and integration-related descriptors, such as radial flux, axial flux, coreless, or frameless. The following overview adopts this established terminology and summarizes the most relevant motor design concepts used in humanoid robots. The listed motor types do not constitute mutually exclusive classes, but rather represent dominant design and integration approaches that are frequently encountered in humanoid actuation systems.

Electric motor technologies (not exhaustive):

Magnetic flux topology

1. **Radial-flux motors** feature a rotor rotating inside a stator with radially oriented magnetic flux. They represent the most mature and widely adopted motor topology in humanoid robots, offering a robust balance between torque capability, efficiency, manufacturability, and cost. Radial-flux motors have a high rotor inertia and experience more cogging effects, which can limit their dynamic responsiveness. However, they are the dominant choice for medium and high-load humanoid joints due to their technological maturity.

2. **Axial-flux motors** employ magnetic flux oriented parallel to the axis of rotation, enabling compact axial dimensions and high torque density. Their low inertia and short axial length make them attractive for highly integrated and space constrained joint designs. However, increased manufacturing complexity, sensitivity to rotor stator alignment, and thermal management challenges currently limit their use in humanoid robots to experimental platforms and niche applications.

Electromagnetic construction

3. **Iron-core motors** use laminated stators with slotted windings and represent the predominant electromagnetic construction for medium and large humanoid joints. The iron-core enables high torque capability, good thermal conductivity, and mechanical robustness, which are critical for load bearing joints such as hips, knees, and shoulders. These benefits come at the expense of increased inertia and cogging torque compared to coreless designs, but are generally acceptable where continuous torque and durability are prioritized.

4. **Coreless motors** eliminate the iron core by employing self-supporting windings, resulting in extremely low rotor inertia and smooth torque output. This enables fast dynamic response, high efficiency, and precise controllability, making coreless motors well suited for small and medium sized joints such as fingers, wrists, and dexterous manipulation mechanisms. Their limitations include lower achievable torque, reduced thermal robustness, and higher manufacturing costs due to complex winding structures and permanent magnet usage.

Mechanical integration

5. **Frameless motors** comprise only stator and rotor components and are directly integrated into the joint structure without an external housing. This integration approach enables compact actuator designs with reduced mass and inertia while improving mechanical stiffness and thermal coupling. Frameless permanent magnet motors are therefore widely used in high load humanoid joints, particularly hips, knees, and shoulders. The main challenges are increased integration complexity, strict alignment requirements, and higher design and manufacturing effort associated with custom interfaces and thermal management.

Beyond the motor concepts discussed above, additional actuation technologies such as linear motors or alternative electromagnetic principles are occasionally considered in robotic systems. Due to limitations in force density, cost, integration effort, or technological maturity, their use in humanoid robots remains largely confined to niche or experimental applications. Consequently, permanent magnet based rotary motors continue to represent the dominant actuation technology across the majority of humanoid joints. Table 6 summarizes the key properties, typical applications, limitations, technical maturity for humanoid operation, and representative industrial suppliers of the discussed electric motor design concepts.

Table 6: *Summary of motor hardware assessment. 1) Technical maturity derived from technology readiness level (TLR) for humanoid operation. Technical maturity: low-maturity (1/4), mid-maturity (1/2), high-maturity (3/4), fully mature (1).*

Motor Hardware (not exhaustive)

Motor type	Key properties	Application	Key limitations	Technical maturity[1]	Key players (Not exhaustive)
Radial-flux motors (with iron core)	Highly mature and widely adopted	Medium & high load joints	Inertia & torque density	●	Unitree (CN), Nidec (JP)
Axial-flux motors	Decreased rotor inertia & very high torque density	Mainly prototype legs	Manufacturing maturity & cost, durability	◑	Magnax (NL), YASA (UK), EMRAX (SI)
(Radial-flux) Coreless construction	High precision & efficiency	Hands & precision joints	Power density & durability	◕	Maxon Motor (CH), Portescap (US), Nidec (JP)
(Radial-flux) Frameless integration	Compact & robust design	Large high load joints	Integration complexity, cost & manufacturing	●	Kollmorgen (US), Lin Engineering (CN)

3.3. Actuation Layer - Reducers

Reducers play a central role in humanoid actuation systems, as they translate motor torque and speed into joint-level motion, while directly affecting efficiency, precision, weight, and durability. In humanoid robots, reducers must support highly dynamic movements, frequent load reversals, and compact joint integration under strict mass and space constraints. While strain wave, planetary, and cycloidal reducers are well established in precision machinery and mobility applications, their transfer into humanoid architectures involves distinct trade-offs. All three reducer types are industrial proven and available, and therefore represent the most common choices in current humanoid designs. In particular, the integration of a low gear planetary reducer with a frameless motor is a frequently employed configuration for high torque joints, and is often referred to as a quasi-direct drive.

Reducer technologies (not exhaustive):

1. **Strain wave reducers,** also known as harmonic drives, provide very high reduction ratios while maintaining minimal backlash and extremely high torsional stiffness. They consist of a wave generator, a flexspline, and a circular spline, working together to transmit motion precisely and smoothly. These properties make strain wave reducers particularly suited for elbow, wrist, and finger joints, where precise positioning and fine control are critical, as well as for knees, hips, and other high-load joints when combined with high-torque motors. Their compact and lightweight design reduces overall limb inertia and mass, improving energy efficiency, agility, and dynamic response. Limitations include finite torque capacity, efficiency losses that increase with higher reduction ratios, and flexspline fatigue under continuous high loads. Custom integration for humanoid-specific joints adds further complexity and cost.
2. **Planetary reducers**, also called planetary gearheads, are widely used in humanoid robots where moderate to high torque amplification is required with relatively high efficiency. They consist of a central sun gear, multiple planet gears mounted on a carrier, and an outer ring gear. This arrangement allows the input torque to be distributed among several gears, providing high torque capacity and compact design. Planetary reducers are often used in shoulder and hip joints, where a

combination of high torque and moderate precision is sufficient, and in fast-moving joints that require efficient power transmission. Compared to strain wave reducers, planetary reducers generally have higher efficiency and greater torque capacity, but they usually exhibit more backlash and lower torsional stiffness, which can reduce positional accuracy in fine-motion applications.

3. **Cycloidal reducers** use an eccentric input and rolling cycloidal disc to achieve high single-stage reduction ratios, with near-zero backlash and excellent shock-load resistance. They provide high torque density, making them well-suited for humanoid hips, knees, ankles, and torso joints, where compact design, high positional accuracy, and rigidity are critical. Limitations include vibration at high speeds, high manufacturing costs, and sensitivity to lubrication, while custom integration for humanoid-specific joints adds further complexity.

Table 7 summarizes the key properties, applications, limitations, technical maturity for humanoid operation, and the key players of the explored reducer technologies.

Table 7: *summary of reducer hardware assessment. 1) Technical maturity derived from technology readiness level (TLR) for humanoid operation. Technical maturity: low-maturity (1/4), mid-maturity (1/2), high-maturity (3/4), fully mature (1).*

Reducer Hardware (not exhaustive)

Reducer type	Key properties	Application	Key limitations	Technical maturity[1]	Key players (Not exhaustive)
Strain wave reducer	High precision, zero backlash, compact	Elbow, wrist, fingers, hips	Torque limits, wear, efficiency losses, cost	◕	Harmonic Drive (JP/US), Maxon Motor (CH), Nabtesco (JP)
Planetary reducer	High torque capacity, efficient, compact	Shoulder, hip, fast-moving joints	Backlash, lower torsional stiffness, wear	●	Wittenstein (DE), Neugart (DE), Schaeffler (DE)
Cycloidal reducer	Torque density, low backlash, shock load capacity	Load bearing joints	Complexity, efficiency, cost	◕	Onvio (US), Bonsystems (KR), Nabtesco (JP)

3.4. Structural and energy layer - Batteries

Energy storage is a key constraint for the autonomous operation of humanoid robots. Battery systems determine achievable runtime, system mass, and operational flexibility, as humanoid robots rely on fully onboard energy storage while operating under strict constraints on weight and available installation space.

Current humanoid models use lithium-ion battery cells that support ~2-4 hours of humanoid operation per cycle. This is sufficient for demonstrating humanoid robots. However, in an industrial setting, where downtime is costly and battery-swapping technologies are economically challenging, developing high-energy, next-generation batteries specifically for humanoid robots is imperative. Several battery chemistries aim to increase energy density; the most promising are solid-state batteries.

Battery technologies (not exhaustive):

1. **Lithium-ion batteries** that are currently used in humanoid robots were originally developed for new energy vehicles. These batteries typically use an LFP, NMC, or NCA cathode combined with a graphite or graphite-silicon composite anode. Such off-the-shelf battery cells offer sufficient energy density (~200 Wh/kg) for demonstration purposes, but not enough energy for industrial use cases.

2. **Solid-state batteries** replace the liquid electrolyte with a solid electrolyte, enabling the use of a lithium metal anode. This can increase energy density up to >500 Wh/kg, which is well above the practical design limit of current Li-ion cells. In theory, solid-state batteries offer higher energy capacity, a longer cycle-life, and greater safety. Several companies, such as QuantumScape, Solid Power, Lyten, and Blue Solutions, are promoting solid-state technology such as lithium-sulfur, and establishing manufacturing sites. The need for higher energy densities at the cell level in automotive applications has diminished due to innovative pack concepts, such as cell-to-pack designs. Thus, humanoids present a major opportunity for solid-state manufacturers.

Table 8 summarizes the key properties, applications, limitations, technical maturity for humanoid operation, and the key players of the explored battery technologies.

Table 8: *summary of battery hardware assessment. 1) Technical maturity derived from technology readiness level (TLR) for humanoid operation. Technical maturity: low-maturity (1/4), mid-maturity (1/2), high-maturity (3/4), fully mature (1).*

Battery Hardware (not exhaustive)

Battery type	Key properties	Application	Key limitations	Technical maturity[1]	Key players (Not exhaustive)
Lithium-ion	High cycle life and low self discharge	Humanoid energy system	Insufficient energy densities for humanoid	◕	CATL (CN), Samsung (KR), FinDreams (CN), LG (KR)
Solid-state	Increased safety, high energy densities	Humanoid energy system	Production cost and ionic conductivity	◑	Lyten (US), QuantumScape (US), Solid Power (US), BlueSolutions (FR)

4. Humanoid Hardware Cost Model

Building on the hardware architecture and component assessments presented in the previous sections, this section introduces a hardware cost model for humanoid robots that enables a structured comparison across different cost scenarios.

The cost model provides a consolidated hardware cost baseline for humanoid robots and focuses exclusively on hardware components. The model is based on a bottom-up, component-level analysis across sensing, actuation, structural and energy systems, and dexterous hands, which together constitute the core hardware cost structure of humanoid robots (Section 2). The components are clustered into low-cost, mid-cost and high-cost categories. All cost assumptions reflect low-volume or prototype-level production. Scale effects are therefore not considered at this stage. Dexterous hands are treated as a separate hardware category. Although they could theoretically be decomposed into actuation, sensing, and structural and energy elements, this approach is impractical for the cost model, as dexterous hands are typically sourced as complete subsystems from robotic OEMs or specialized manufacturers.

The humanoid hardware cost model does not include assembly costs and software-related costs and therefore does not represent the total humanoid production cost.

The sensing layer accounts for the lowest share of total hardware costs. The main cost drivers for medium- and high-cost humanoids are the edge SoC, LiDAR, and depth camera. The sensing layer in the cost model does not include the tactile sensors used for the dexterous hands.

The actuation layer of humanoid robots, particularly reducers, motors, and bearings, is a primary cost driver in humanoid hardware systems. Low-cost actuation components are inexpensive off-the-shelf motors and reducers capable of actuating a demonstration humanoid. However, these components do not provide the necessary quality to address real-world use cases in industrial or non-industrial settings. High-quality actuation hardware from tier-one manufacturers increases costs by up to a factor of 10.

The structural and energy layer costs are strongly influenced by the manufacturing costs of sophisticated aluminum alloy structures for the knees, elbows, etc. The use of advanced lightweight materials, such as magnesium and titanium, further increases the cost of the structure. Battery costs account for only a small portion of the total costs, which is notably different from NEVs. However, the humanoid structure offers significant cost reduction potential, as manufacturing costs can be reduced through economies of scale and the use of high-performance materials, such as fiber-reinforced composites and polymer-based structural and surface materials.

Dexterous hands are the single most cost-driving hardware element in a humanoid robot. Achieving the manipulation of a human hand is considered one of the key challenges in humanoid robotics. In our cost model, five-finger dexterous hands are treated as purchased components, meaning that the reported values reflect typical market prices rather than underlying low-volume hardware manufacturing costs. The most sophisticated models offer ~24 degrees of freedom and easily cost more than 70.000 USD. Lower-cost alternatives, however, typically fail to meet the cycle life and durability requirements necessary for industrial applications.

In Figure 7, the hardware procurement costs of a low-cost, medium-cost, and high-cost humanoid are shown.

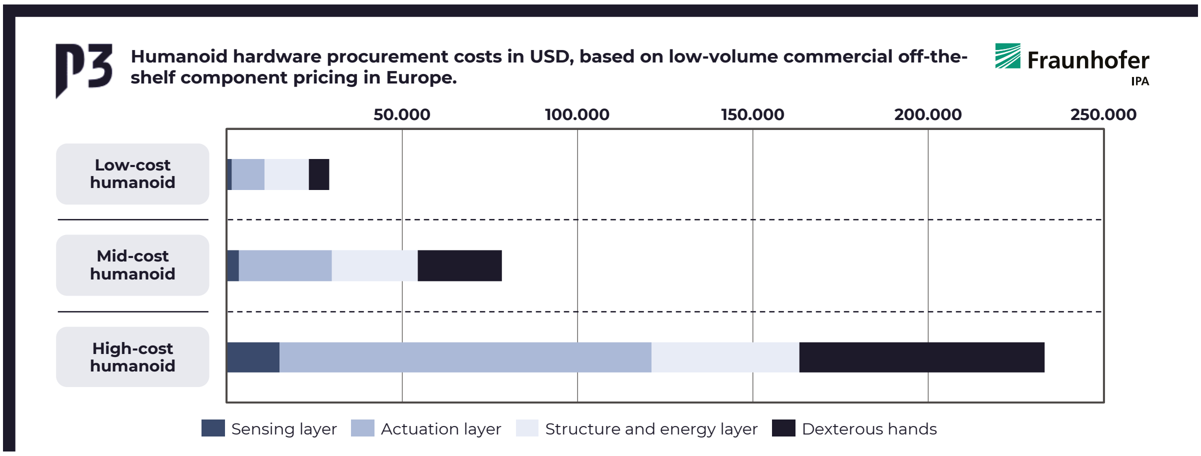

Figure 7: *Estimated humanoid hardware cost in USD based on humanoid cost model. The cost assessment is based on low volume hardware procurement cost in 2026 and sourcing for the European market.*

5. Can European Manufacturing Capitalize on the Humanoid Momentum?

The current momentum of humanoid robotics is often framed as a software-driven revolution. However, this whitepaper demonstrates that the economic viability, scalability, and industrial impact of humanoid robots will also be determined by hardware. Actuation, energy storage, sensing, and structural components dominate system cost, reliability, and lifetime and therefore define whether humanoids remain demonstrators or become productive industrial assets.

Europe and other advanced economies are well positioned to capture value from this transition. Unlike previous platform shifts that were dominated by digital ecosystems, humanoid robots depend on high-value mechatronics, precision manufacturing, and industrialization capabilities that closely match European strengths. The critical question is not whether humanoids will be deployed, but where and by whom their hardware value chain will be industrialized.

Realizing this opportunity requires coordinated action across industry, policy, and research.

Three key takeaways

For industry

Humanoid robotics represents a new high-value hardware market, not merely an extension of existing automation. Suppliers who engage early in actuators, reducers, batteries, dexterous hands, and lightweight structures can shape future reference architectures and secure long-term positions in emerging supply chains. The window of opportunity lies before hardware platforms and sourcing strategies fully consolidate. Companies should move beyond pilot projects and actively invest in product roadmaps, manufacturability, and partnerships with humanoid OEMs.

For policymakers

The largest share of value creation in humanoid robotics lies in hardware, not software. Industrial policy that focuses exclusively on AI risks missing the main economic leverage point. Targeted support for hardware focused research, scale up of precision manufacturing, and de-risked pilot production is essential to anchor humanoid value creation in Europe. Lessons from battery cell manufacturing underline the importance of early, coordinated investment to avoid long-term dependency on non-European suppliers.

For research

Current research efforts are strongly concentrated on learning, control, and perception algorithms. While these advances are essential, hardware-specific challenges remain under addressed. Topics such as energy efficient actuation, long lifetime reducers, robust tactile sensing, charging concepts, and humanoid-specific battery systems offer high scientific relevance and immediate industrial impact. Research that integrates hardware design, system integration, and operational constraints will be critical to bridge the gap between laboratory prototypes and industrial deployment.

European industries need to act now

Humanoid robotics is approaching a decisive phase. The next few years will determine whether Europe becomes a core industrial player in humanoid hardware or remains a downstream adopter. Strategic alignment between manufacturing expertise, public funding, and application-driven research can turn the current momentum into sustainable industrial value creation. The opportunity is tangible, but it requires action now.

Interested for More Insights? Feel free to Contact the Authors of this Paper!

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