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Transformation

Physical AI, part 2: Humanoid robots

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Key takeaways

- AI is redefining robotics, enabling a new generation of humanoid robots that can perceive, learn and act autonomously in the physical world. After decades of incremental progress, the field has reached a turning point, with breakthroughs in generative AI and large language models accelerating the rise of "embodied intelligence" and reshaping expectations for what service robots can accomplish.
- The humanoid robot population is poised for take-off. BofA Global Research projects that the number of humanoid units in operation could reach three billion by 2060, surpassing cars on a per-capita basis. While industrial and service applications are expected to lead adoption in the near term, household humanoids are projected to accelerate quickly and ultimately account for the largest share - 62% - by 2060.
- In part 2 of our physical AI series, we outline what you need to know about humanoid robots - including how they work, how they're being used today and key challenges the industry faces as it moves toward large-scale deployment.

Humanoid robots 101

Humanoid robots are a type of service robot designed to move, perceive and interact in ways that resemble human beings. As a type of physical AI, they embody artificial intelligence in a dynamic, mechanical form capable of acting on the world (for readers new to this topic, Physical AI, part 1: The basics provides a helpful foundation). This enables them to operate in complex, unstructured environments, rather than controlled settings. Unlike traditional service robots, which are built for narrow, repetitive tasks, humanoids are required to navigate real-world spaces, interpret human behavior and respond through physical action – placing far greater demands on AI for sensing, motion control and natural-language interaction.

After decades of incremental progress, the field reached a turning point in 2023, as breakthroughs in generative AI and large language models (LLMs) accelerated the emergence of "embodied intelligence." By giving AI a physical form, humanoid robots can learn directly from the world, translate language into action and adapt to people in real time – reshaping expectations of what robots can do.

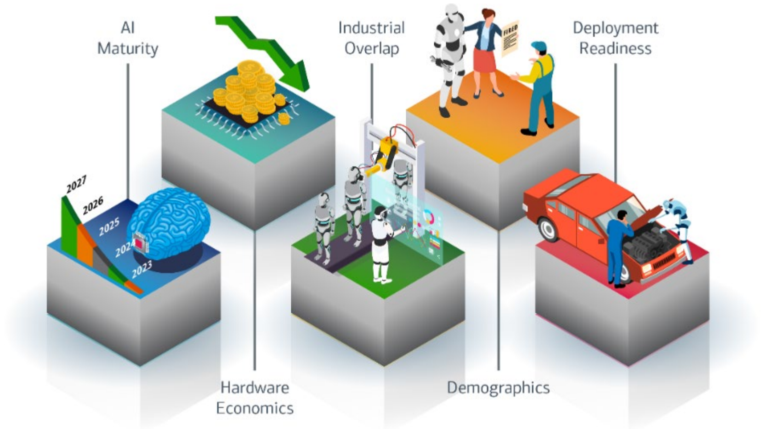
Humanoid adoption is accelerating – but why?

According to BofA Global Research, humanoid robot adoption is speeding up (Exhibit 1), mainly because of:

1. **AI maturity**: Model breakthroughs are now enabling more general-purpose learning, better long-term reasoning and more reliable AI operation in unstructured, real-world human environments.
2. **Hardware economics**: Rapid cost declines and improvements across key humanoid components (e.g., batteries, motors, sensors, actuators and onboard AI compute) have lowered the required bill of materials (hardware costs) and boosted overall feasibility of humanoids.
3. **Industrial overlap**: Humanoid robots can tap into existing supply chains, manufacturing methods and capital investment from electric vehicles (EVs), autonomous tech and AI hardware sectors, helping them scale faster and reduce execution risk.
4. **Demographics**: Ongoing labor shortages, aging workforces, wage inflation and high turnover make flexible robotic labor economically appealing across industries, such as manufacturing, logistics and services, even before humanoids fully match human abilities.
5. **Deployment readiness**: Humanoid form factors fit with existing tools, buildings, and workflows, which cuts down on deployment barriers. Together, improved safety, autonomy and self-learning reduce integration, regulatory and operating friction.

Exhibit 1: Tech breakthroughs, economics and demographics are key drivers behind humanoid adoption

Infographic illustrating factors accelerating humanoid robot adoption



Source: BofA Global Research

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Scaling-up from pilot to production

The robot rush: Increased investment is happening now

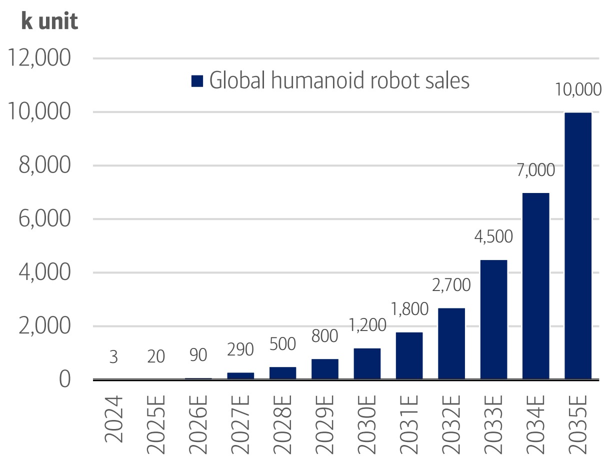
The commercial race to develop humanoids is heating up as the tech matures and prices decline. Investments have risen sharply – from $0.7 billion in 2018 to $4.3 billion in 2025.[1] And as of January 2026, over 50 companies were in the process of building their own humanoids,[2] with 150 commercial launches to date.[3] So far, the development landscape has bifurcated between companies vertically integrating robots in their own factories and those selling or renting humanoids to their customers.

A robot population boom is on the horizon

BofA Global Research forecasts annual humanoid robot shipments will surge from 20,000 units in 2025 to 10 million by 2035, implying an 86% compound annual growth rate (CAGR) (Exhibit 2). In 2026 alone, sales are expected to reach 90,000, as leading companies ramp up production capacity and scale deployments.

Exhibit 2: Annual humanoid robot shipments are projected to reach 1.2 million in 2030 and 10 million by 2035

Annual global humanoid robot shipments (thousands (k))



Source: BofA Global Research

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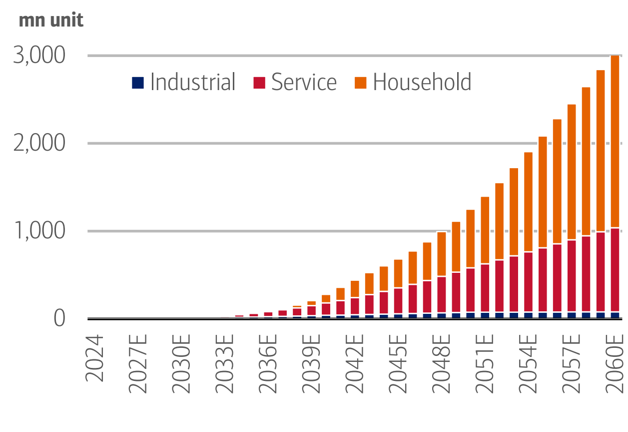
Exhibit 3: The humanoid robot "population" could reach three billion by 2060E

Long-term forecast of humanoid robot units in operation (UIO) by application (millions (mn))



Source: BofA Global Research

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[1] Humanoid Guide. (2026). *Humanoid robot guide*.

[2] Botfino. (n.d.). *Humanoid Robotics Company Intelligence*.

[3] Humanoid Guide. (2026). *Humanoid robot guide*.

As seen in Exhibit 3, the global "robot population" could reach 300 million by 2040 and even three billion units by 2060 – outnumbering cars per capita. While analysts believe industrial and service applications are likely to come first, by 2060 they project household humanoids will make up the largest share (62%, or two billion units).

Economies of scale and tech breakthroughs will significantly reduce costs

Despite recent improvements, the total bill of materials (BOM) or hardware cost of humanoid robots remains relatively high, with pilot-stage development ranging from $90,000 to 100,000 per unit. However, standardizing product specifications has already brought costs down considerably, with further reductions possible with economies of scale. For example, BofA Global Research estimates a built-in China humanoid robot's BOM cost was $35,000 in 2025 but expects it to be roughly cut in half to below $17,000 by 2030, driven by scale effects and continued improvements in component design.

How do humanoid robots work?

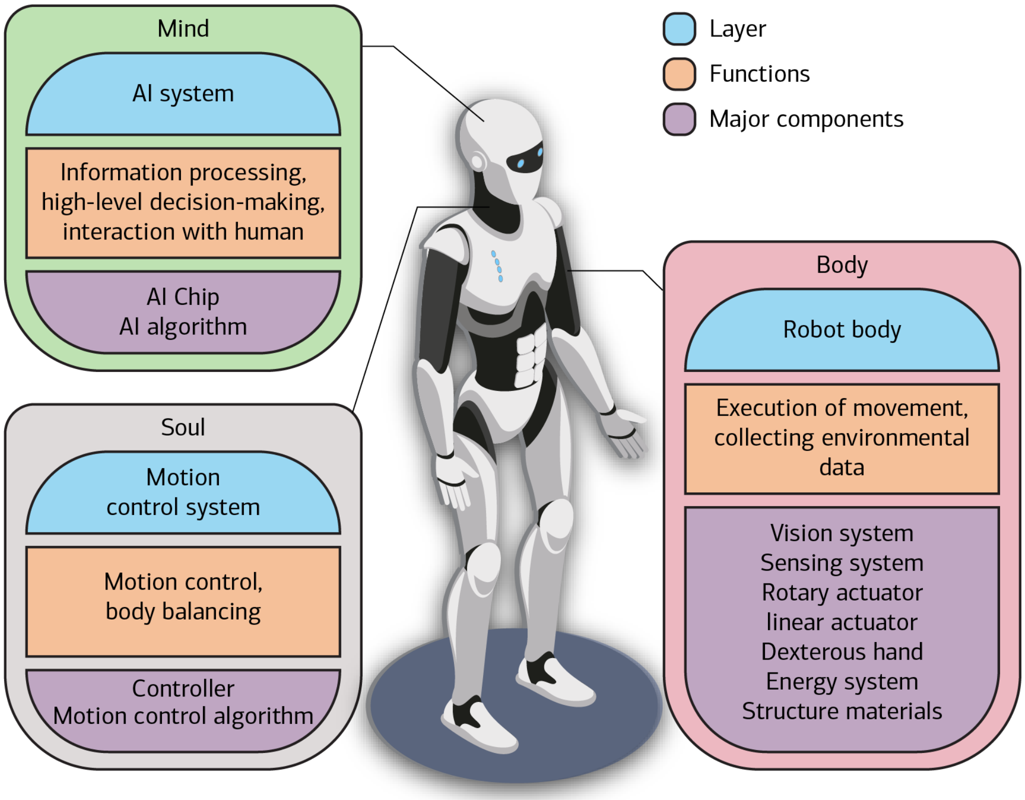
Humanoid robots operate by combining central AI control and compute with mechanical components – actuators, motors, reducers, hands and sensors – to turn intelligence into physical action. While AI systems perceive and decide, high-performance compute processes information in real time, and tightly integrated actuators and sensors deliver balance, dexterity, strength and safe interaction. Together, these elements form the foundation of capable, scalable humanoid autonomy.

Integrating the "mind, body and soul"

The structure of a humanoid robot can be framed as the hardware and software that collectively create the "mind, body and soul" (Exhibit 4). The mind refers to the AI system, which handles high-level cognition, such as environmental understanding, task planning, model inference and interaction with humans. The body of the humanoid comprises the physical components, including vision and sensory systems, actuators, dexterous hands, energy systems and structural materials. And last, the soul represents the motion control system – the robot's internal coordinator – responsible for balance, movement planning and motion execution.

Exhibit 4: A combination of AI chips and algorithms make up the humanoid's mind and soul, with multiple components required for the body – such as actuators, motors, batteries and sensors for vision

Infographic illustrating the mind, body and soul of humanoid robots



Source: BofA Global Research

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Bot mechanics

From components to capability

Humanoid robots are built from a tightly integrated combination of computing, actuation, sensing and mechanical components that together enable perception, movement and interaction in real-world environments (Exhibit 5). Rather than operating independently, these elements must be synchronized in real-time, with performance evaluated by how effectively intelligence, motion and hardware constraints are integrated. For a more in-depth discussion of humanoid components, check out our prior publication: Humanoid robots 101.

Exhibit 5: Advances in AI and motion control, combined with precision hardware, such as actuators and motors, are the core tech embedded in humanoid robots

Infographic illustrating key components in a humanoid robot

Component		What it does	Why it matters
Control System (AI + Motion Control)		Interprets the world, decides what to do, and coordinates how the robot moves.	Determines how intelligent, safe, and adaptable the robot is in real-world, human environments.
AI Computing & Chips		Provides the processing power needed to run perception, reasoning, and control in real time.	Sets the ceiling on capability, responsiveness, and autonomy; critical for moving from demos to deployment.
Rotary Joint Actuators		Drive rotational movement in joints like shoulders, elbows, hips, and wrists.	Core to mobility and manipulation; quality of integration determines smoothness, precision, and noise.
Linear Joint Actuators		Enable extension and compression in joints such as knees, ankles, and arms.	Essential for strength, balance, and lifting; heavily influences stability and payload capacity.
Dexterous Hands		Allow the robot to grasp, hold, and manipulate objects, including delicate items.	Unlocks household, service, and fine assembly tasks; one of the hardest and most valuable capabilities to replicate.
Reducers (Mechanical Gearing)		Convert motor speed into usable torque for precise joint movement.	Critical for accuracy, durability, and safety; a key differentiator between industrial-grade and prototype robots.
Torque Motors		Deliver compact, high-power movement directly at the joints.	Enable lighter, faster, and more responsive robots with fewer mechanical compromises.
Sensory System (Touch, Force, Balance)		Helps the robot feel contact, understand forces, and maintain balance.	Enables safe interaction with people

Source: BofA Global Research

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Achieving higher degrees of freedom

Advances in dexterous robotic hands are expanding what humanoids can manipulate in real-world settings. A key driver is higher degrees of freedom (DoF) – the number of independent axes of movement across a robot's joints – which directly determines how precisely and flexibly it can position its limbs, hands and fingers. These gains are amplified by fully rotational joints that can turn continuously through 360°, rather than stopping at human-like anatomical limits.

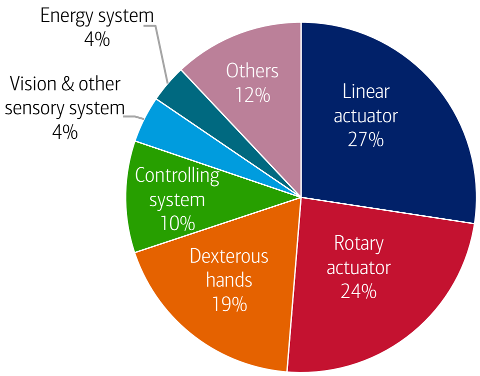
Alongside this, compliant actuators – motors designed to yield under force rather than remain rigid – allow robots to absorb impacts, regulate force and adapt safely when grasping or interacting with uncertain objects. Combined with tactile-sensing and learning-based control, higher DoF and compliance materially increase *usable* dexterity. However, according to BofA Global Research, progress remains constrained by limited high-quality manipulation data and the difficulty of replicating human-level dexterity and improvisation.

Bill-of-material economics: Actuators are actually expensive

The actuation system is the muscle of a humanoid robot, controlling movement, balance and force. The system integrates motors, drives, transmissions and sensors into compact modules that are deployed across both rotary and linear joints. A humanoid typically uses dozens of actuators, underscoring their central role in performance and cost.

By 2030, BofA Global Research projects that linear actuators – which enable extension and compression in humanoid joints – will account for the largest BOM share (27%), followed by rotary actuators (24%) and dexterous hands (19%) (Exhibit 6).

Exhibit 6: Actuators account for more than 50% of the total BOM cost
BOM cost breakdown (by module/system, 2030)



Source: BofA Global Research

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Humanoid use cases

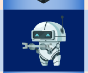
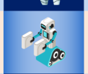
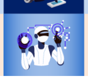
In an aging, labor-constrained global economy, BofA Global Research believes humanoid robots could offer an increasingly cost-competitive form of physical labor, underpinned by improving AI autonomy and manufacturing scale.

From the factory floor to in-home assistants

Humanoid robots are being deployed in a growing range of applications (Exhibit 7). In manufacturing, automotive and warehouse environments, they handle tasks related to moving materials, inspection and assembly. In retail, hospitality and live events, they support customer interactions, restocking and front-of-house services. Emerging applications also include healthcare, homes and education, where humanoids are positioned for assistance, monitoring, training and learning support. Together, these developments reflect a gradual shift from structured industrial settings towards more human-centered environments.

Exhibit 7: From cars to caring – humanoids have a wide variety of use cases
Infographic illustrating humanoid robot use cases

Humanoid Robot Use Cases

Use Case		Description
Manufacturing		Performing industrial assembly, machine tending, and materials-handling tasks.
Warehousing & Logistics		Handling picking, packing, palletizing, and goods movement in distribution settings.
Automotive		Supporting assembly lines, component handling, and factory-floor operations in automotive production.
Retail & Hospitality		Delivering customer greeting, wayfinding, and front-of-house assistance.
Special-Purpose/ Events		Executing demonstrations, exhibitions, performances, and specialised showcase tasks.
Healthcare & Support		Carrying out non-clinical assistance, supply movement, and routine operational tasks in care environments
Home Assistance		Assisting with household chores, tidying, and simple object-handling tasks.
Education & Research		Supporting simulation, training, experimentation, and human-robot interaction studies.

Source: BofA Global Research

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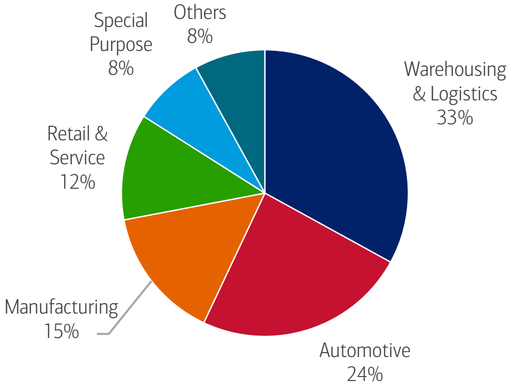
So far, initial humanoid use cases have been mostly industrial and are expected to remain that way in the near term. By 2027, Counterpoint Research estimates that 72% of installations will be in logistics, manufacturing and automotive (Exhibit 8).

Exhibit 8: Initial humanoid use cases are industrial
Humanoid use cases in 2027, by industry (%)



Source: Counterpoint Research, BofA Global Research

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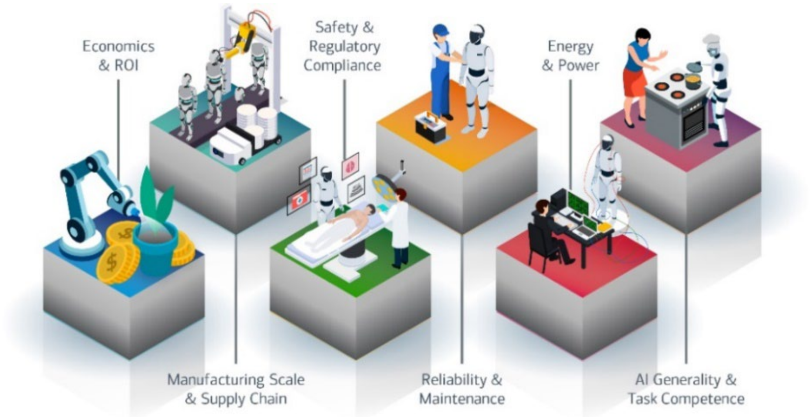
It's tough being a humanoid

As manufacturing volumes of humanoids increase, the challenges facing companies building and deploying them are shifting from production to techno-economic – achieving the levels of performance, reliability and cost that make sense commercially. The challenges to scaling humanoids, according to BofA Global Research, are (Exhibit 9):

- **Economics and return on investment (ROI):** High unit costs, uncertain labor substitution benefits and expensive repairs make it difficult to achieve compelling payback periods.
- **Manufacturing scale and supply chain maturity:** Some humanoid parts, like actuators, sensors, reducers and batteries, lack the volume, reliability and cost structure needed for large-scale humanoid production.
- **Safety, certification and regulatory compliance:** Standards for safe human-robot co-working are still emerging, slowing approvals for real industrial deployment.
- **Reliability, uptime and maintainability:** Current humanoids remain too fragile and maintenance-intensive for 24/7 industrial environments that demand high uptime and durability.
- **Energy and power constraints:** Limited battery life and immature charging or hot-swap ecosystems restrict continuous operation and reduce productivity.
- **AI generality and task competence:** Autonomous systems still struggle with unstructured, variable, real-world tasks, limiting the economic usefulness of humanoids today.

Exhibit 9: Challenges remain ahead of commercial operation of humanoid robots at scale
Infographic illustrating key challenges behind scaling humanoid robots



Source: BofA Global Research

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Disclosures