

THE PRINTED BODY

The Printed Body: How Far Additive Manufacturing Reaches into a Humanoid, Joint by Joint

Nine of the ten subsystems inside an electric actuator have a demonstrated additive route. The tenth is the drive die, and it must be fabbed.

David Jean Charlot, PhD

Dean of Physical AI · The Charlot Lab, Institute for Physical AI @ BMI

Correspondence: contact@physicalai-bmi.org · physicalai-bmi.org · The Charlot Lab:
labs.physicalai-bmi.org/charlot

Interactive companion: physicalai-bmi.org/research/charlot-lab#topic-printed

ABSTRACT. A humanoid you can print is governed by one honest question: what can additive manufacturing actually do, joint by joint, and where does it hit a wall. This report treats an electric actuator as ten subsystems — structure, compliant transmission, flexure bearings, soft-magnetic iron, copper windings, permanent magnets, insulation, thermal path, sensing, and the power-electronics drive die — and asks, for each, whether a published additive route exists. Nine do. The tenth, the drive die, must be fabbed rather than printed. A printed humanoid is therefore not a printed shell with bought muscles: in the Free Humanoid Corpus every joint is one axial-flux actuator, AXF-1, re-sliced from a single design so that only the diameter changes between joints. The report also states the cost of full printability plainly, using the corpus's design-study figures: printed bonded magnets deliver roughly half the remanence of sintered magnets, so torque density is roughly halved; a lean 14-degree-of-freedom walker carries on the order of ten kilograms of actuators; and the mass penalty for printing the legs instead of buying them is about +38 percent of actuator mass. Every one of these numbers traces to one cheap coupon, the remanence of a printed magnet, and every joint is priced in joules on the MathGround substrate. The research effort is released CC0 as prior art. No original experiments are reported.

1. Introduction

Two open-source humanoids have recently made a printed body ordinary rather than exotic. Berkeley Humanoid Lite is a low-cost, customizable robot whose structure is three-dimensionally printed^[1], and ToddlerBot is an open, machine-learning-compatible platform

built from accessible, largely printed parts^[2]. Both demonstrate that the frame, the linkages, and much of the mechanical body can come off a desktop printer. Both also buy their muscles: the actuators are commercial servo modules, whose rotors, stators, and power electronics are made by conventional, capital-intensive processes.

That boundary is exactly where the interesting question lives. If the frame is printable but the actuator is not, then a printed humanoid is a printed shell around bought muscles, and its sovereignty — the fraction of the machine a small lab can make for itself — stops at the motor mount. This report asks how far additive manufacturing actually reaches into the actuator, subsystem by subsystem, and where it hits a wall. The question is answered honestly, meaning that each subsystem is credited only where a published additive route exists, and the one part that resists printing is named rather than glossed.

The answer this report defends is specific. An electric actuator decomposes into ten subsystems. Nine of them have a demonstrated additive route in the peer-reviewed literature. The tenth, the semiconductor drive die at the heart of the motor controller, must be fabricated in a wafer fab and cannot be printed by any near-term method. The consequence is a design in which the body and the muscles are made the same way, from the same printer, and only one small silicon part is bought in.

2. Scope and method

This is a review and a research position, not an experimental paper. It surveys published additive-manufacturing routes for the components of an electric machine and organizes them against a single actuator architecture. It reports no original measurements. Where the report states a quantity — a torque ratio, an actuator mass, a mass penalty — that quantity is a figure from the design study internal to the Free Humanoid Corpus, and it is labeled as such. These are design-study numbers derived from published material properties and first-order sizing, not validated bench measurements. The report is explicit about maturity throughout: several of the additive routes it credits are laboratory demonstrations rather than production processes, and the integrated printed actuator at humanoid load is a design target of the corpus, not a delivered part. The corpus, including the AXF-1 actuator family described here, is released under CC0 as prior art.

3. Ten subsystems, and where additive manufacturing reaches

An electric rotary actuator is not one object but a stack of functions: something to hold shape and react load, something to reduce speed and raise torque, something to let the shaft turn, something to carry and shape magnetic flux, something to make current, something to make field, something to keep the current where it belongs, something to move the heat out, something to know the angle, and something to switch the power. Table 1 lists these ten subsystems, the additive route for each, and its maturity. Figure 1 shows the same result as a map of the actuator: nine subsystems in the printable set, one outside it.

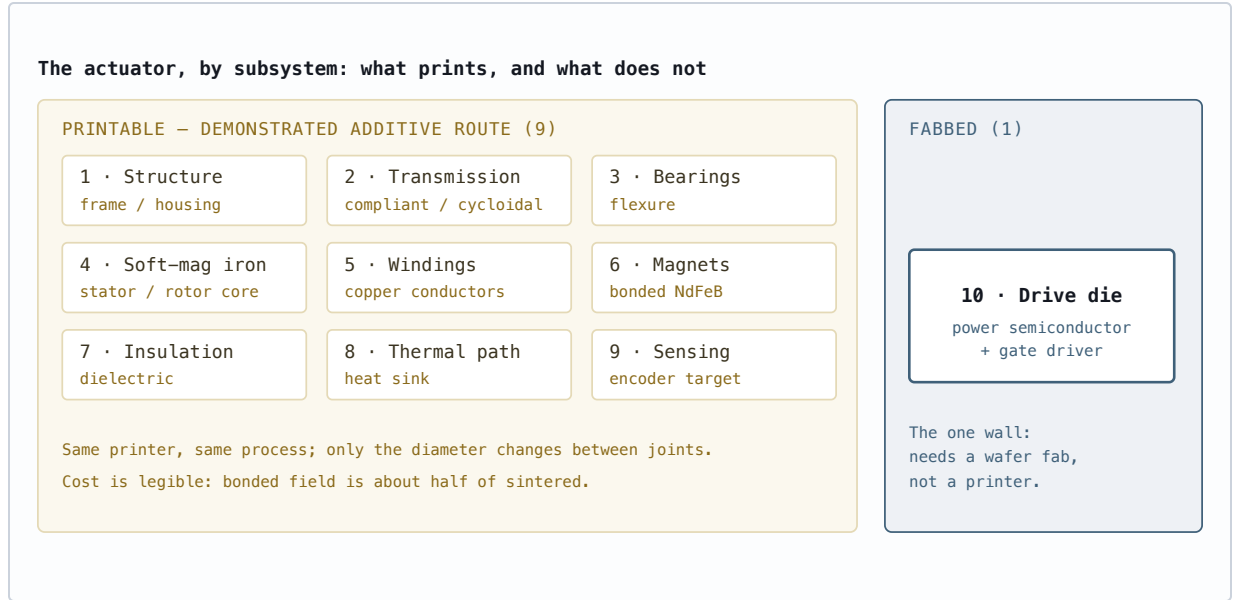


Figure 1. The ten subsystems of an electric actuator. Nine (left) have a demonstrated additive route and are made on the same printer; the tenth (right), the power-electronics drive die, is the single part that must be fabricated. An interactive version is at physicalai-bmi.org/research/charlot-lab.

The two subsystems that carry the magnetic circuit deserve a note, because they are where the doubt usually sits. Soft-magnetic iron, which shapes and carries the field in the stator and rotor cores, has a maturing additive route: reviews of additive manufacturing of soft-magnetic materials for electrical machines catalog printed cores and their magnetic performance^[3], and process work has produced graded soft-magnetic material directly from non-magnetic powders^[4]. Permanent magnets, which supply the field, are printable as bonded magnets: large-area additive manufacturing of high-performance bonded neodymium-iron-boron magnets is demonstrated in the literature^[5]. National-laboratory programs on additive manufacturing of electric machines cover the windings, cores, and thermal structures together and place the whole machine, minus its controller silicon, inside the additive envelope^[6].

Table 1. The ten subsystems of an electric actuator and their additive route. Maturity is the report's own reading of the cited literature.

#	SUBSYSTEM	FUNCTION	ADDITIVE ROUTE	MATURITY
1	Structure	hold shape, react load	printed polymer / metal frame & housing ^[1,2]	routine
2	Transmission	reduce speed, raise torque	printed compliant / cycloidal stage	demonstrated
3	Bearings	let the shaft turn	printed flexure bearings	demonstrated
4	Soft-magnetic iron	carry / shape flux	printed stator & rotor cores ^[3,4]	maturing
5	Windings	make current	printed copper conductors ^[6]	early
6	Magnets	make field	printed bonded NdFeB ^[5]	demonstrated
7	Insulation	keep current in place	printed dielectric layers	demonstrated

8	Thermal path	move heat out	printed heat-sink structures ^[6]	demonstrated
9	Sensing	know the angle	printed encoder targets / magnetic sensing marks	demonstrated
10	Drive die	switch the power	none — requires a wafer fab	fabbed

4. One actuator family: AXF-1, re-sliced per joint

If the actuator is printable, the natural next move is to stop treating each joint as a bespoke motor selection and instead print one actuator, parameterized. The Free Humanoid Corpus does this with a single axial-flux design, AXF-1. Axial-flux permanent-magnet machines put a flat disc rotor across an axial air gap from the stator, which gives a short, high-torque package that suits a printed, pancake form far better than a long radial-flux motor^[7]. AXF-1 fixes the pole count, the coil topology, the magnet grade, and the print process, and exposes one primary parameter: the active diameter. A hip joint and a wrist joint are then the same actuator at two diameters, sliced from the same design, printed on the same machine, wound the same way.

The engineering payoff of one family is that every part, every tolerance, and every failure mode is shared across the robot, so a fix at one joint is a fix everywhere. The scaling is close to first-order. For an axial-flux machine the air-gap torque scales with the active area and the air-gap flux density, and the air-gap flux density is set by the remanence of the magnets. Holding the aspect ratio fixed and sweeping the diameter D gives, to first order,

$$T \propto B_r A_{\text{gap}} \propto B_r D^2.$$

This is the whole reason one design covers the whole robot: the joints that need more torque are simply the larger-diameter slices, and the magnet grade — the term B_r — is held constant across all of them. It is also the reason the choice of magnet is not a detail but the hinge of the entire machine, which the next section makes explicit.

5. The legible cost of full printability

Full printability is not free, and the corpus's discipline is to make its cost legible rather than to hide it. The cost enters through the magnets. A sintered neodymium-iron-boron magnet reaches a remanence on the order of 1.2–1.4 tesla; a bonded magnet, in which magnetic powder is held in a printable polymer binder, reaches roughly 0.6–0.7 tesla, because binder displaces magnetic material^[8,9]. In the corpus's design study the bonded magnet used for AXF-1 is taken to deliver about half the remanence of the sintered part it replaces. By the torque relation above, at equal geometry the printed actuator makes about half the torque of a bought one.

The design carries that penalty openly rather than compensating in secret. To hold a required joint torque with half the torque density, the active mass must roughly double, either by growing the diameter or by stacking material. In the corpus's design study a lean 14-degree-of-

freedom walker built entirely from AXF-1 slices carries on the order of ten kilograms of actuators. The comparison that matters is not against some ideal motor but against the same robot with bought actuators: printing the legs instead of buying them costs about **+38 percent of actuator mass** in the design study. The report states these as the corpus's design-study figures, not as validated bench measurements.

This is the sovereignty tax. It is the mass a small lab pays to make its own muscles instead of importing them, and it is a real weight the walker must carry every step. The corpus's position is that a legible +38 percent is a better thing to own than a hidden dependency, because the tax is a number you can attack — with better bonded-magnet loading, with graded cores, with a lighter transmission — whereas a supply relationship is not.

The whole cost of full printability is a single physical quantity: the remanence of a printed magnet. Halve it and the torque halves, the active mass doubles, and the sovereignty tax appears. Recover it and the tax shrinks. The design study is arranged so that this one term is the lever.

6. Every number traces to one coupon

Because the entire cost funnels through magnet remanence, the corpus grounds its numbers in one cheap measurement: a printed-magnet coupon whose remanence B_r is read on a bench. That single coupon propagates. Through $T \propto B_r$ it sets the torque of every joint. Through the torque-to-mass relation it sets the ten-kilogram actuator budget and the +38 percent tax. Nothing in the ledger is asserted independently of it; the coupon is the root of the tree.

The ledger itself is kept in joules, not in newton-metres, and is evaluated on the MathGround substrate. Each joint is priced by the mechanical work it must deliver over a gait cycle and the electrical energy that printed actuator draws to deliver it, given its remanence-limited torque constant. Pricing joints in joules rather than in torque makes the printed and bought designs comparable on the axis that a battery actually cares about, and it lets the sovereignty tax be read as an energy penalty per step rather than only as a mass penalty. The accounting is deterministic: the same coupon and the same gait yield the same joule figure for a joint every time it is evaluated, which is what makes the design study auditable by anyone who reprints the coupon.

$$m_{\text{active}} \propto \frac{T_{\text{req}}}{B_r} \quad \implies \quad \Delta m_{\text{sovereignty}} = \sum_{\text{joints}} \left(\frac{B_r^{\text{sint}}}{B_r^{\text{bond}}} - 1 \right) m_{\text{active}}^{\text{bought}}.$$

The right-hand side is the mass ledger the corpus reports: a sum over joints of the extra active mass each printed actuator carries because its printed magnet is weaker, and it is this sum that evaluates to about +38 percent in the design study. Every symbol on the right resolves, eventually, to the one coupon on the left.

7. Discussion: the unoccupied axis

The open printed humanoids that motivate this report occupy a clear and useful position: a printed body around bought muscles, accessible and reproducible^[1,2]. The axis this report points at is the one they leave open, a printed *actuator* at humanoid load, which is not the same claim as a printed *robot* and is harder. The evidence assembled here is that the components are individually within the additive envelope — printed cores^[3,4], printed bonded magnets^[5], printed windings and thermal structures^[6] — and that the axial-flux form factor^[7] is the one that integrates them into a printable package. What the corpus contributes is the integration and the honest ledger, not a new physical demonstration.

The wall is genuine and should not be talked around. The drive die — the power semiconductor and its gate driver — requires a wafer fabrication line and will not be printed by any near-term method. A printed humanoid is therefore a nine-of-ten machine, and the honest claim is exactly that: everything but the switching silicon can be made in-house, and the switching silicon is bought as a small, well-understood, low-mass part. Naming the one fabbed subsystem is more useful than pretending it away, because it tells a lab precisely what it still depends on.

The corpus is released CC0, without patent, as prior art. The intent is defensive: to keep the printed actuator at humanoid load in the public domain so that the obvious design cannot be enclosed. The claims here are a research position and a set of design-study figures, not product specifications, and the report marks the printed actuator at load as a target of the corpus rather than a delivered part.

8. Conclusion

Additive manufacturing reaches nine of the ten subsystems of an electric actuator. It reaches the structure, the transmission, the bearings, the soft-magnetic iron, the windings, the magnets, the insulation, the thermal path, and the sensing. It does not reach the drive die, which must be fabbed. A humanoid built on this fact is not a printed shell with bought muscles but a machine whose muscles are printed too, one axial-flux family re-sliced per joint. The price of that sovereignty is legible and single-valued: printed magnets carry about half the field, so a lean 14-degree-of-freedom walker carries on the order of ten kilograms of actuators and pays about +38 percent in actuator mass, all of it traceable to one printed-magnet coupon and all of it priced in joules. Those are the corpus's design-study figures, offered as prior art rather than as validated results, so that the one honest question — how far does the printer reach — has a public, auditable answer.

References

1. Q. Liao, et al. Demonstrating Berkeley Humanoid Lite: An Open-source, Accessible, and Customizable 3D-printed Humanoid Robot. arXiv:2504.17249, 2025.
2. H. Shi, et al. ToddlerBot: Open-Source ML-Compatible Humanoid Platform for Loco-Manipulation. arXiv:2502.00893, 2025.

3. M. Garibaldi, et al. A Review of Additive Manufacturing of Soft Magnetic Materials in Electrical Machines. *Machines* 11(7):702, 2023. doi:10.3390/machines11070702.
4. Gradient soft magnetic materials produced by additive manufacturing from non-magnetic powders. arXiv:2109.05947, 2021.
5. L. Li, A. Tirado, et al. Big Area Additive Manufacturing of High Performance Bonded NdFeB Magnets. *Scientific Reports* 6:36212, 2016. doi:10.1038/srep36212.
6. National Renewable Energy Laboratory. Manufacturing Advanced Electric Motors and additive manufacturing of electric machines (MADE3D program). U.S. Department of Energy, nrel.gov.
7. J. F. Gieras, R.-J. Wang, M. J. Kamper. *Axial Flux Permanent Magnet Brushless Machines*. Kluwer Academic / Springer, 2005. doi:10.1007/1-4020-2720-6.
8. Compression bonded NdFeB permanent magnets. In: *Modern Permanent Magnets*, Elsevier, 2022. doi:10.1016/B978-0-323-88658-1.00007-8.
9. The status of sintered NdFeB magnets. In: *Modern Permanent Magnets*, Elsevier, 2022. doi:10.1016/B978-0-323-88658-1.00010-8.

AI-use disclosure. Preparation of this report used a large language model (Claude, Anthropic) for drafting and editing text, organizing the reviewed literature, and preparing the figures and the interactive companion. Cited references were checked to resolve to their sources. The author reviewed the content and is solely responsible for it. Consistent with ICMJE, COPE, and IEEE guidance, the model is a tool and is not credited as an author.

Institute for Physical AI @ BMI · The
Charlot Lab
503 McKeever Rd, Arcola, TX 77583, USA
physicalai-bmi.org · contact@physicalai-
bmi.org

Technical Report TR-2026-15 · Preprint v1
© 2026 Institute for Physical AI @ BMI.
Released for open scholarly use. No proprietary or novel experimental results
are reported.