Institute for Physical AI @ John Bailey Institute · The Charlot Lab

MOTION · BIOLOGICAL ENERGETICS

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Six Ways a Body Cheats

The mechanisms human movement uses to make acrobatics affordable, five of them priced against an identified power model, and the four predictions of ours that the pricing falsified.

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Companion to TR-2026-41, which priced a strike. This one prices the strategies a body uses to make such things affordable. Five single-file benches, every prediction registered before its run.

`cost of force, not cost of work` `a latch beats a motor by 3.5x`

`variable stiffness is worth 0.3%` `latency inverts damping`

Humanoid robots now perform acrobatics, and they do it at a cost of transport roughly sixteen times a human's [3]. The gap is usually read as a control problem. This report reads it as an energetics one and asks which of the mechanisms biology uses actually transfer. Six are surveyed and five are put on a bench sharing the loss model of TR-2026-41. The organising result is that **a body and an electric motor pay for the same thing, and it is not work**: a runner's metabolic rate tracks the inverse of foot-contact time, the rate at which force is generated [2], and an actuator's dominant loss is copper, proportional to torque squared. Both are cost-of-force. Every mechanism that helps therefore either removes force from an actuator or removes the time it must hold it, and the benches order them accordingly, which is not the order the literature suggests. Letting structure carry the standing load saves a factor of 3.5 over ten seconds of standing, because holding body weight costs an actuator 20 W of copper while doing no work at all. Variable stiffness from geometry, which we had called the most under-exploited idea available, is worth 0.3% against a free and physically impossible oracle. Reorientation in free fall is mechanically free to numerical precision and far too slow to replace a reaction wheel. Control latency does not merely blunt an impedance, it inverts it: a damper acting on velocity from a fifth of a cycle ago pumps energy in, and beyond a

critical delay no gain recovers the loss. Four of our own registered predictions were falsified, and the falsifications are reported rather than removed.

1. What question does this report ask?

Humanoid robots have become athletic. They box, tumble, run and land. What they have not become is cheap: the standing comparison remains a dimensionless cost of transport near 3.2 for a computing biped against 0.2 for a walking human [3]. The same study built a passive-dynamic machine that matched the human figure, which is the fact that reframes the problem. A body whose geometry does most of the walking spent what a human spends. The gap was not a controller gap.

So the question here is narrow and answerable: of the mechanisms a human body uses to make dynamic movement affordable, which ones transfer to a machine, and by how much? Six are surveyed. Five are benched. The sixth, muscle acting as a near-isometric strut, is reached indirectly by two of the others and is discussed rather than measured.

2. What do a body and a motor actually pay for?

Kram and Taylor established that the rate of metabolic energy use in running is predicted by body weight and the time available to generate force in each step, measured as foot-ground contact time [2]. Metabolic rate goes as the inverse of that time. It is a cost of GENERATING FORCE, not a cost of doing work.

An electric actuator's dominant loss is copper, torque squared over the motor constant squared. Work does not appear in it. A drive holding a static load at zero velocity, doing no work whatsoever, is still paying.

The organising fact. Both systems are priced on force, not on work. It follows that the mechanisms which save energy are not the ones that reduce how much work is done. They are the ones that lower peak force, shorten how long force must be held, or obtain the force from something that is neither muscle nor motor. Every section below is an instance of that sentence, and the ordering it produces is not the one a reading of the biomechanics literature suggests.

3. Who should carry the standing load?

A muscle holding an isometric force consumes energy continuously; a bone under the same load consumes none. The machine version of that distinction is measurable. On the loss model used throughout, holding body weight for a 35 kg leg costs 20 W of copper while producing no motion and no work.

Three answers were benched on one leg with one spring and one travel budget: the spring carries the standing load, the actuator carries it, or a mechanical latch carries it [10].

Standing time	Spring holds	Motor holds	Latch holds	Cheapest
0 s	29.1 J	18.5 J	18.9 J	motor, barely
1 s	35.1 J	44.6 J	24.9 J	latch
10 s	89.1 J	278.9 J	78.9 J	latch, by 3.5x

The actuator wins for a quarter of a second and loses permanently thereafter. The passive spring loses too, for a different reason: it sags. Static deflection is weight over stiffness, and at 3000 N/m a 35 kg body has consumed 95% of a 12 cm travel budget before anything lands on it. Removing that sag by latching the standing load returns the travel as absorbable energy: 105% more at 4000 N/m, 11% at 9000, 1% at 30000.

This is the sharpest transfer on the page and the least glamorous. It also explains a familiar asymmetry: a person can stand all day and cannot hold a squat for five minutes, because standing is carried by skeleton and a squat is carried by muscle.

4. What is a spring for, and what is an actuator for?

Running is a bounce rather than a series of pushes. The arch of the foot stores about 17 J per step and the Achilles tendon 30 to 40 J at running speeds [1], and tendon stores roughly 20 times more energy per kilogram than spring steel [7], at 90 to 93 percent resilience. A steel spring holding an Achilles worth of energy would outweigh the leg.

The benched question is what happens at the boundary of that capacity [11]. A leg with a spring and a yielding actuator was met with landings of increasing depth.

Arriving energy	Spring takes	Actuator yields	Copper	Spring alone
30 J	30.0 J	0.0 J	0.0 J	absorbs it, free
64.8 J	64.8 J	0.0 J	0.0 J	absorbs it, free
99.8 J	64.8 J	35.0 J	19.3 J	bottoms out
119.8 J	64.8 J	55.0 J	30.3 J	bottoms out

Below the spring's capacity the actuator contributes nothing and costs nothing. Above it, the actuator is the only thing that works, at 0.55 J of copper per joule absorbed against zero for the spring. That is a division of labour rather than a compromise: size the elastic element to the routine case and the actuator to the exceptional one. Tendon for the stride, muscle for the stumble.

5. Is variable stiffness from geometry worth anything?

Extending the toes at push-off winds the plantar fascia around the metatarsal heads, tightening the arch exactly when it must transmit force [8]. The foot is compliant on landing and rigid at push-off, and nothing commands the change. Pennate muscle shifts its own gear ratio with load by the same kind of trick [5]. We expected this to be the most transferable idea available, since robots buy variable stiffness with a second motor and biology appears to get it from kinematics.

To bound what any such scheme could win, an ORACLE was benched: stiffness chosen freely per hop, no mass, no idle, no retuning cost, physically impossible [9]. Across a 4.5-fold range of hop heights it wins 0.3%, and a genuinely actuated variable-stiffness leg finishes 18% worse after paying real overhead.

The reason is that a bounce costs a term proportional to the inverse square root of stiffness plus a term proportional to its square root. Gravity puts a force floor under the entire contact, so the floor term rises as the spring softens while the dynamic term falls. There is a genuine interior minimum and it is shallow: under 10 percent variation across a factor of eight in stiffness. Near the optimum the energy does not care what the stiffness is.

> What binds instead is sag, which is Section 3's constraint arriving in a different costume. A spring soft enough to be cheap cannot hold the body up. A passive spring serves two masters and one stiffness cannot be right for both. Biology declines the trade rather than optimising it: the tendon sits in series with an active element that sets the operating point, so muscle carries the standing load while the tendon handles only the dynamics. The windlass is best understood not as a stiffness schedule but as evidence that something upstream decides where the spring operates.

6. Can a body turn in mid-air for free?

A dropped cat lands feet-first having never possessed any angular momentum. Nothing is violated: momentum stays zero and ORIENTATION, which is not conserved, changes. A cyclic change of shape produces a net change of orientation, a geometric phase of the kind that precesses a Foucault pendulum. Kane and Scher modelled it in 1969 [6].

The physics supplies an exact control for the bench, which is rare and worth stating. A system whose joint axes are all PARALLEL cannot do this at all: planar angular momentum is holonomic, orientation is a function of shape alone, and a closed loop in shape space returns the body to precisely where it began. The simulator returns 0.000e0 degrees in that case and 0.877 degrees for skew axes, with momentum held at 1e-16 [12]. Driving both joints in phase traces a line segment enclosing no area and returns 0.0000 degrees from identical path length, which is the clearest evidence available that the effect is geometry and not effort. Net mechanical work over the closed loop is 0.0000 J.

It is nonetheless the wrong tool for a fast turn. The rotation arrives in instalments of roughly two degrees per cycle, so a quarter turn requires 38 cycles which do not fit inside a half-second flight, at 3161 J of copper against a reaction wheel's 3.6 to 36 J.

The lever is mass distribution, not control. Net turn per cycle runs from 0.01 degrees when 5 percent of the inertia is in movable limbs to 2.36 degrees at 60 percent, a 236-fold range. A cat is mostly swingable. A humanoid carrying a battery in a rigid trunk cannot turn in the air whatever its controller does, and the two mechanisms are complementary rather than competing: shape change is slow, mechanically free and never saturates, while a wheel is fast, costly and must be desaturated.

7. What does control latency cost?

A muscle's force-velocity relationship means that a perturbation stretching it faster meets more resistance immediately, because that is the material's response. Brown and Loeb named this a PREFLEX [4]: a correction arriving before any nerve has fired, since no nerve is involved. A robot's compliance is a control law, and the same intended impedance arrives late.

Benched on one limb with the intended damping held fixed and only its timing varied, the effect is not a gradual tax [13]. A damper acting on stale velocity opposes where the limb WAS, and once the delay is a meaningful fraction of the oscillation period that force begins to point the wrong way.

Delay	Of period	Peak (mm)	Energy pumped IN	Stable
0 ms	0%	13.2	0.000 J	yes
15 ms	5%	14.7	0.002 J	yes
50 ms	18%	19.3	1.342 J	yes
80 ms	28%	diverged	162.0 J	no

Gain buys the lost rejection back for a while and then stops being able to. Matching the undelayed limb's peak costs 1.12 times the copper at 5 ms and 1.53 times at 15 ms; at 30 ms and beyond, **no gain reaches it**, because raising gain brings the instability forward.

The variable that decides this is not the delay in milliseconds but the delay as a fraction of the limb's own period. One fixed 20 ms loop is harmless on a postural hold at 900 N/m, seven percent of a cycle behind, and diverges on a limb stiff enough to strike with at 9000 N/m, where it is twenty-three percent behind. The preflex is therefore not a general advantage. It is an advantage exactly where movement is fast, which is where acrobatics, martial arts and landings live.

8. Where does this sit against what is already built?

This report's references were, in its first version, entirely biological, and that was a real omission for a report whose whole question is which biological mechanisms transfer to a machine. Every mechanism priced above has a machine-side literature, and two of them have a mature one. Naming it is not a formality: it is what tells a reader which of the numbers above are a rederivation and which are a joining.

The standing load (Section 3) is established engineering, and the strongest prior art in this report. Clutched and quasi-passive elastic actuators exist precisely because holding a static load costs a motor continuous current for no mechanical work. Capstan-amplified electroadhesive clutches [17] mechanically ground a joint so that the drive supplies no holding torque at all, on the stated reasoning that an electrostatic hold draws far less electrical power per unit holding torque than a motor does. Section 3's latch is that idea, and its 3.5-fold result over ten seconds is *conservative* against that work, because it charges the latch arm for the strike as well as the hold. What Section 3 adds is the price in this series' units, on this body, against the same loss model as everything else. It does not contribute the mechanism.

Elastic storage (Section 4) is the most thoroughly built of all of them, and this report says least about its literature. Series-elastic and parallel-elastic actuation are a standard part of legged-robot design, and the division of labour Section 4 prices, a spring carrying what it can and an actuator paying only above the spring's capacity, is the reasoning those designs were built on. Section 4 contributes the price of crossing that boundary, 0.55 J of copper per joule absorbed above capacity, and not the boundary itself. This review did not survey that literature, and Section 4 should be read as a measurement inside a settled design idea.

The spine question (TR-2026-41 [16], restated here) has prior art pointing both ways, and the direction matters. This review located, but did not read, work on compliant spine mechanisms for humanoid locomotion [19], and takes no figure from it. What it did read is the abstract of the most recent active-spine work: S-Cheetah [18] reports a three-degree-of-freedom active spine reaching 6.9 m/s in a rotary gallop, a 7.2 rad/s in-place turn, and an emergent aerial self-righting capability. That abstract states no energy result; this review did not read the full paper and so makes no claim about what it reports elsewhere. What can be said is narrow and still worth saying: the case that abstract makes for a spine is a case about *agility*, not about joules, and TR-2026-41 reaches the ordering *feasibility and agility before efficiency* from the pricing side. Two arguments pointing the same way is not corroboration, since one of them is a silence, but it does mean this series' conclusion is not in tension with how the most recent spine hardware is being sold.

The boundary is the task, and that is the reconciliation. Where spine work reports energy gains, this review found it reported for locomotion, which is cyclic and gravity-dominated. This series prices an impulsive momentum-delivery task in copper under a fixed actuator-mass budget, where the bill is set by peak torque replicated down a serial chain. Those are different loadings of the same structure and there is no reason to expect one answer to hold for the other. This review did not locate a study that prices both on one body, which is what would settle it; until one exists, neither result should be carried onto the other's task without being rerun there.

Latency and impedance (Section 7) sit inside control theory's oldest result. That delay bounds achievable loop gain is not news; what Section 7 contributes is the scaling statement. The cost is set by delay as a fraction of the limb's natural period rather than in milliseconds, which is why the same actuator is adequate on one limb and not on another.

Two more mechanisms have machine-side literature this review did not read: variable gearing in pennate muscle has robotic analogues in variable-transmission and variable-stiffness actuators, and mid-air reorientation is a solved problem in spacecraft attitude control, where the same zero-angular-momentum holonomy is standard. Neither is claimed as new here. **This report claims no novel mechanism.** What it claims is the comparison: six mechanisms surveyed and five put on a bench, one body, one identified electrical loss model, priced against each other so that a transfer ordering can be stated at all, with every prediction each bench registered before its run scored in public and the four that fell kept in Section 10 rather than edited out.

9. Which of these transfer, and in what order?

Mechanism	What it buys	Measured
Structure carries the standing load	Holding torque goes to zero	3.5x at ten seconds
Elastic storage	Peak power and peak current	free below capacity; 6.4x peak reduction in TR-2026-41
Multiarticular transfer	Joint count stops costing	bill follows actuator count, TR-2026-41
Variable gearing from geometry	Almost nothing, on energy	0.3%; claim withdrawn
Preflexes	Impedance that cannot be late	no gain substitutes past 11% of a period
Conserved momentum in flight	Slow, free, non-saturating turn	real; too slow to replace a wheel

The order is not the one we expected. What looked most promising, variable stiffness obtained from pure geometry, is worth a third of a percent. What looked most obvious, letting structure hold the standing load, is worth a factor of three and a half. The mechanisms that win are the ones that remove force from an actuator or remove the time it must hold it, which is Section 2 restated, and it took four wrong predictions to keep rediscovering.

10. What did we predict wrongly?

Every bench registered its predictions before its run. Four fell, and they are more useful than the ones that held.

Predicted	Measured	What it taught

Variable gearing is the most under-exploited idea available	Worth 0.3% against a free oracle	Build the oracle FIRST, so the prize is bounded before any mechanism is credited or blamed for collecting it.
Softer springs are always cheaper, bounded only by travel	There is an interior minimum	The hand derivation ignored gravity's force floor. An independent analytic probe disagreed with the simulator, and the simulator was right.
Regeneration cannot substitute for eccentric muscle economy	It cut the bill 88%	A dominance ordering is a property of a REGIME, not of a loss model. Copper dominates a strike and does not dominate a large-displacement absorption.
Free-fall reorientation needs no reaction wheel	38 cycles for a quarter turn	Free is not fast. The physics claim was right and the engineering claim was wrong, and only the cycle count separated them.

A fifth correction was procedural rather than physical. The absorbable envelope was first scored as maximum drop height, on which the sagging passive spring appeared to WIN. That is correct arithmetic and a misleading measure: a leg with more travel falls further during the landing, and that descent is itself gravitational energy to absorb. Scored as energy absorbed, which is the capacity actually under test, the ordering reverses. Same physics, opposite headline, and the difference lay entirely in what was scored.

11. Conclusions

A body is not efficient because its muscles are good engines. It is efficient because most of what looks like work is arranged not to be paid for: skeleton holds the posture, tendon carries the stride, geometry supplies the turn, and material response supplies the fast corrections that a control loop would be too late to make. Each of those is a way of keeping force off an actuator, or keeping it there for less time, and both a metabolism and a motor are billed on exactly that.

The transfer is uneven and the ranking is not intuitive. The cheapest wins available to a machine are structural and unglamorous. The most elegant mechanism surveyed, variable stiffness produced by the geometry of a motion already happening, does not pay in energy at all, though the reason it does not is itself the discovery: it was never a stiffness schedule, it was evidence of an active element deciding where the spring operates. And one mechanism does not transfer at any price with current parts. A preflex is not a fast controller. It is the material's own response, and past roughly a tenth of a limb's period no amount of gain reproduces it.

12. The forcing function

What is bounded	The physics that sets it	The engineering change that moves it	What becomes possible
An actuator holding a static load burns 20 W for no work, forever	Copper is torque squared and is indifferent to velocity, including zero velocity	A mechanical detent, brake or over-centre linkage that carries posture without the drive	3.5x on a standing duty cycle, and the freed travel returns as absorbable landing energy, over 100% more at soft stiffnesses
A passive spring must both hold the body up and absorb the landing	Static sag is weight over stiffness, and it consumes travel before anything happens	An active element in series setting the operating point, which is the muscle-tendon arrangement	The soft spring becomes usable at all, and elastic storage stops competing with posture for the same travel
Impedance delivered later than a tenth of a limb's period cannot be recovered by gain	A damper acting on stale velocity opposes where the limb was, and adds energy once the motion has reversed	Impedance that is a material property rather than a control law: series compliance, tuned damping, variable-stiffness materials	Fast limbs become stable without a race against the loop, and the compute budget stops being spent on what a material could do
Reorientation in flight arrives at about two degrees per shape cycle	A geometric phase is a flux through enclosed area in shape space, and the	Move inertia outward into limbs that can swing; 5% to 60% limb share	In-flight orientation control with no reaction wheel and no saturation, for

	area is bounded by limb travel	is a 236x change in turn per cycle	robots whose mass is not locked in a rigid trunk

13. Scope and limits

Every benched figure is MODELLED, not metered. The loss form is the identified electrical power model of a real robot arm [14] and its magnitudes are calibrated against a 71.5 J reach measured on physical hardware [15]; no hardware was involved in any number reported here as benched. Elastic return figures from the literature vary with speed, surface and subject, and the per-step values quoted are for running. The energy contribution of fascia beyond tendon and plantar structures is contested and nothing here rests on it. Cost-of-transport comparisons depend on what is counted, and the humanoid figure is an estimate from published specifications rather than a metered measurement [3]. The variable-stiffness ENVELOPE question, as distinct from its energy question, took six runs of which five were defeated by terms the model was missing rather than by the mechanism, and it is reported as open. Muscle's force-velocity curve is nonlinear and is modelled as a linear damper, which understates the biological side. Finally, none of this establishes that a machine built like a body would be efficient: the companion report found that copying the kinematics of a spine without copying its actuation makes matters dramatically worse [16].

> **Run it rather than read it.** The benches behind Sections 3 through 7 and their run receipts are released under CC0 at huggingface.co/datasets/physicalai-bmi/punch-energetics. Single-file Rust, no dependencies. Each file opens with its registered predictions, including the ones that fell.

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