

Biohybrid Actuators Combining Living Cells and Photopolymer Structures: Force Generation, Feeding, Control and Longevity

Qualification of muscle-driven and cell-powered actuation coupled to printed structural elements

Juan Seguro

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Correspondence: info@3Dresyns.com · www.3Dresyns.com

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Abstract

Biohybrid actuators use living contractile cells or tissues to generate force against an artificial structure. Photopolymer components can provide anchors, skeletons, guides, molds or encapsulating interfaces, but actuation is a system property that depends on tissue maturation, feeding, stimulation, load transfer and fatigue. This review defines qualification of force, displacement, geometry, stimulation, culture support and lifetime, and prevents attribution of biological actuator performance to the photopolymer structure alone.

Keywords: biohybrid actuator; skeletal muscle; photopolymer; 3D printing; force; stimulation; feeding; fatigue; longevity

1. Significance and scope

Living muscle tissues can serve as soft actuators whose force and adaptability differ fundamentally from conventional motors. Printed polymer structures provide alignment, anchors and load paths, but the living tissue remains the power source. This distinction is essential when photopolymer fabrication is used to shape the skeleton or anchor geometry. Reviews of cell-actuated biohybrid robotics likewise frame performance as an integrated problem of living actuator, artificial structure and control rather than as a material property of either component alone [1].

Biohybrid actuation should be separated from passive deformation caused by swelling, temperature or medium exchange. A no-cell or non-contractile control can establish the mechanical background of the printed structure. The active output should then be expressed against tissue size, geometry and load so that changes in actuator architecture are not mistaken for changes in intrinsic muscle performance.

2. Force generation depends on tissue state

Contractile force evolves with cell differentiation, alignment, maturation and loading history. Force should therefore be reported with tissue age, dimensions and stimulation protocol. A displacement measurement without load information cannot establish actuator force, while peak force alone does not describe usable stroke or work.

Force measurements should state whether the actuator is isometric, isotonic or operating against a defined compliant load. Different boundary conditions produce different force and stroke values. Normalising force only by nominal tissue cross-section can also be misleading if maturation or compaction changes that cross-section over time, so the method used to estimate active area should be reported.

Force should also be normalized to a clearly defined geometric basis when comparisons are made. Cross-sectional area, tissue width, cell number and anchor spacing can all change apparent performance. Work and power can be more informative than peak force alone when an actuator drives a real load, but they require synchronized force-displacement-time measurements. A large unloaded stroke and a high isometric force are different operating points and should not be merged into one performance claim.

3. Interface and load transfer can dominate device motion

The connection between muscle and artificial structure must transmit force without slip or excessive local stress. Morita and co-workers arranged multiple skeletal muscle tissues within a tensegrity structure and demonstrated multi-directional actuation, showing that architecture determines how biological contraction is converted into device motion [2]. Interface failure can therefore limit performance even when the tissue remains viable.

Load-transfer interfaces should be inspected after cycling because fatigue can occur at the tissue-anchor junction even when neither the bulk tissue nor the printed skeleton has failed. Snap-fit or molded anchor geometries can reduce handling damage, but they also create stress concentrations. Morita, Morimoto and Takeuchi illustrate how structural architecture converts multiple tissue contractions into multi-axis motion [2], making the artificial skeleton part of the actuator transfer function.

4. Feeding and oxygen delivery limit scale

Living tissue requires continuous nutrient and oxygen supply and removal of waste. Increasing tissue thickness raises diffusion limitations and can produce central necrosis. Designs that bundle multiple thin tissues can increase total force while preserving transport.

Ren, Morimoto and Takeuchi used multiple muscle tissue actuators to drive a multijointed biohybrid hand, demonstrating a scalable architectural strategy rather than simple enlargement of one tissue [3]. Transport limits should be assessed under the actual duty cycle. Repeated stimulation increases metabolic demand, so a tissue that remains viable at rest can become oxygen-limited during operation.

Medium exchange, perfusion, construct thickness and rest intervals therefore belong in endurance tests. Scaling by simply increasing tissue thickness is especially risky because transport capacity does not scale with volume in the same way as force-producing mass.

Feeding architecture becomes part of actuator design as scale increases. Static medium may be adequate for thin constructs but does not establish performance in thicker or enclosed devices. Perfusion, vascular-like channels or periodic medium replacement should be reported with temperature and gas control. If motion changes transport through cyclic compression or bending, that coupling should be acknowledged rather than treating biological supply as independent of mechanics.

5. Control and stimulation are part of actuator identity

Electrical, optical or chemical stimulation determines activation timing and can influence fatigue. The control signal should be reported as part of the actuator specification, together with response delay and recovery. Selective stimulation can create multiple degrees of freedom, but cross-talk and asynchronous contraction should be tested.

Control qualification should include stimulus amplitude, waveform, duration, frequency and electrode or optical geometry. A stronger stimulus that produces more motion may also accelerate fatigue or tissue damage. Multi-degree-of-freedom systems should additionally report selectivity: the commanded actuator should move while unintended tissues remain below a defined cross-talk threshold.

Control quality should include repeatability and selectivity, not only whether contraction occurs. Threshold, latency, relaxation time, cross-talk between adjacent tissues and adaptation during repeated stimulation can define usable degrees of freedom. Morita and co-workers demonstrate why selective activation is central to multi-directional actuation [2], while later multi-muscle systems show that adding actuators increases both mechanical capability and control complexity [3].

Axis	Measurement	Failure mode
Living actuator	tissue identity, age, viability	force compared across different maturation states
Force/stroke	load, displacement and geometry	motion reported without force context
Interface	attachment and load-transfer integrity	tissue contracts but slips at anchor
Feeding/control	medium, oxygen path, stimulation	short demonstration treated as sustained operation
Longevity	cycles, fatigue, recovery and duration	polymer durability confused with tissue lifetime

Table 1. Domain-specific qualification matrix for biohybrid actuators combining living cells and photopolymer structures.

6. Device-level verification and longevity

Living actuators can fatigue, recover, remodel and change force output with training. Lifetime is therefore not equivalent to polymer durability. Testing should include repeated cycles, rest intervals, force recovery and tissue viability.

Mechanical ageing of the printed skeleton and biological ageing of the actuator should be separated where possible. Longevity should be reported as a time history of force or work, not merely survival duration. A tissue can remain alive while losing useful contractile output.

Recovery after rest, remodelling during culture and changes in passive stiffness should be separated from irreversible degradation of the printed structure. Device-level verification should test the coupled system rather than isolated tissue and skeleton only. The same actuator should be characterised for passive stiffness, stimulated force or displacement, energy or work where meaningful, thermal state, medium condition and post-test tissue viability. ER-439 owns sensor-integrated organ-on-chip measurement and biological interpretation; ER-440 instead treats living tissue as the actuator and qualifies force generation, control and longevity.

Video-derived motion should be calibrated to physical displacement and synchronized with the stimulation record so that timing and phase lag are measured rather than judged visually.

7. Minimum qualification framework

Report cell/tissue identity, maturation protocol, artificial structure material and geometry, interface design, culture/feeding condition, stimulation, force, stroke, response time, cycle count, fatigue/recovery and service duration. If a printed photopolymer is only an anchor or mold, the claim should state that role explicitly rather than implying that the resin itself generates actuation. A minimum qualification framework should include cell source and passage where relevant, tissue dimensions and maturation, printed-material identity and post-cure state, anchor geometry, feeding/oxygen condition, stimulation waveform, load boundary condition, force/stroke, response delay, cycle count, recovery and end-of-test viability.

Scaling claims should state whether increased output came from more tissue, improved tissue-specific force or more effective mechanical transmission.

8. Engineering conclusions

Biohybrid actuation is a systems problem spanning living tissue, transport, control and structural mechanics. Photopolymer structures can improve alignment, assembly and force transmission, but usable performance emerges only when feeding and stimulation preserve the tissue and the interface converts contraction into repeatable motion. Qualification should therefore report biological and mechanical state together over time.

References

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Competing interest

Juan Seguro is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L., which develops and commercialises photopolymer materials and related additive-manufacturing technologies. This review is an engineering analysis and does not constitute a product-performance claim or a device qualification.