

Photopolymer Materials for Soft Robotics: Actuation, Compliance, Fatigue and Multi-Material Constraints in VPP

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Statement of Significance

Soft-robotic performance is an interaction between material constitutive behaviour and actuator architecture. A low Shore hardness does not specify pneumatic bending, a high elongation does not guarantee fatigue life, and a responsive hydrogel does not become a useful actuator without transport, geometry and interface control. This review links VPP material selection to actuation mechanism, hysteresis, creep, permeability, cyclic durability and multi-material integration.

Keywords: soft robotics; soft actuator; pneumatic actuator; elastomer; hydrogel; fatigue; hysteresis; creep; multimaterial; vat photopolymerisation; DLP; 4D printing

Abstract

VPP enables monolithic soft components, complex pneumatic channels and stimuli-responsive architectures, but the relevant material requirements are device-specific. Pneumatic actuators require compliance, tear resistance and low leakage; thermoresponsive or hydrogel actuators additionally require transport kinetics and dimensional stability; self-sensing devices require electrical-mechanical integration; and multi-material robots require durable interfaces between dissimilar networks. Recent DLP research has demonstrated soft pneumatic actuators, local shape-memory and stiffness control, self-sensing thermoresponsive actuators and gecko-inspired anisotropic soft structures [1–5]. This review develops a materials qualification framework based on actuation mode, compliance, fatigue, permeability, hysteresis and interface durability. It separates coupon properties from device outputs and rejects universal bending-angle/pressure maps. Silicone-like 3Dresyn Soft SR grades, NextGen SEA10 and 4Dresyn ETR35 Bio are included as commercial implementation examples without inferring actuator performance from product positioning.

1. Introduction

Soft robots exploit large deformation rather than avoiding it. This changes the material-selection problem from maximising stiffness or strength to controlling compliance, nonlinear response, hysteresis, tear resistance, leakage and fatigue. VPP is attractive because internal pneumatic channels and graded geometries can be printed directly, but highly crosslinked photopolymers can be brittle or viscoelastic in ways that are not captured by hardness alone. These general photopolymerisation and VPP constraints are reviewed in refs [6,7].

2. Actuation classes impose different material requirements

Domain	Measured output	Primary dependency	Claim boundary
Pneumatic/hydraulic	Pressure-displacement response, leakage, burst and cycles.	Modulus, wall thickness, tear resistance, permeability.	Hardness alone does not predict bending.
Thermal / shape-memory	Recovery strain, force, transition and cycling.	Network transition, programming and heat transfer.	One shape-change cycle is not lifetime.
Hydrogel / solvent-responsive	Swelling strain and kinetics.	Diffusion, crosslink density, geometry, environment.	Equilibrium swelling does not define actuation speed.
Electro-thermo responsive	Stimulus-response and electrical heating.	Conductivity, thermal transport, hydration, geometry.	Material responsiveness is not integrated-robot performance.
Hybrid self-sensing	Mechanical actuation plus sensor output.	Interface, conductive pathway, strain transfer.	Sensor coupon response is not closed-loop control.

Table 1. Engineering distinctions that must be preserved.

3. Compliance must be described mechanically

Shore hardness is useful for rapid grouping but does not describe the nonlinear stress-strain response of an elastomeric actuator. Tensile modulus at small strain, secant modulus at operating strain, elongation, tear or fracture behaviour and stress relaxation can all affect motion. Pneumatic bending can also be dominated by wall thickness and chamber geometry. For this reason, material and device characterisation should be separated. Where applicable, tensile qualification should use an exact, reported method such as ISO 527-1/-2 or ISO 37 rather than an unspecified tensile test [8,9].

Coupon property	Device relevance	Missing information	Recommended extension
Tensile curve	Constitutive input for deformation.	Multiaxial and cyclic behaviour.	Large-strain model plus repeat cycles.
Hardness	Convenient compliance screen.	Geometry-specific force/displacement.	Use only as supplementary classifier.
Elongation at break	Maximum monotonic extensibility.	Crack growth and fatigue.	Cyclic strain and tear/fracture test.
Stress relaxation	Force decay at held strain.	Long-term actuator drift.	Relevant temperature/time window.
Permeability / leak	Pressure retention.	Joint/channel defects.	Whole-device leak and burst test.
Swelling	Responsive amplitude.	Kinetics and mechanical strength when swollen.	Time-resolved actuation under service medium.

Table 2. Coupon properties and their device relevance.

4. Pneumatic actuators and leakage

DLP has been used to fabricate soft pneumatic actuators [1], including strategies that combine printing with assisted post-curing to improve internal surfaces. Device qualification should include pressure-displacement response, hysteresis between inflation and deflation, leakage, burst margin and repeated cycling. A bending angle is meaningful only with chamber geometry, pressure, actuation rate and material state. Cross-study angle comparisons without these descriptors are not robust.

5. Stimuli-responsive and shape-changing photopolymers

Semicrystalline acrylate systems can provide local shape-memory and stiffness control [2], while responsive hydrogels can generate deformation through swelling or thermal/electrical stimulus. The controlling timescale may be heat transfer or solvent diffusion rather than intrinsic polymer kinetics. Thin structures can actuate rapidly while thick parts respond slowly even with identical chemistry. Consequently, response time should always be reported with characteristic dimension and environmental condition.

Recent multimaterial DLP work has combined self-sensing and thermoresponsive functions, illustrating the move from passive soft polymers to integrated robotic materials [3]. Gecko-inspired anisotropic structures provide a distinct geometry-process example [4], while machine-learning-guided elastomer design illustrates formulation-level optimisation [5]. These devices add electrical continuity, sensor calibration and interface fatigue to the mechanical problem.

6. Fatigue, hysteresis and creep are primary design variables

Soft actuators repeatedly traverse large strain, making cyclic durability central. Viscoelastic hysteresis converts mechanical work into heat and changes the pressure-displacement loop; creep shifts neutral geometry; stress relaxation reduces blocking force; and small surface defects can grow under repeated inflation. A credible soft-robotics study should therefore include cycles at representative strain/pressure rather than infer durability from high elongation at break.

Failure mode	Material contribution	Geometric/process contribution	Validation
Channel leak	Permeability, under-cure, crack growth.	Thin wall, trapped resin, joint defect.	Pressure hold and leak-rate test.
Tear / rupture	Low fracture energy or fatigue resistance.	Stress concentration at chamber corners.	Cyclic pressure plus failure inspection.
Creep / drift	Viscoelastic network mobility.	Sustained preload or asymmetric geometry.	Repeated zero-position and force tracking.
Hysteresis	Viscoelastic dissipation.	Flow resistance and chamber geometry.	Inflation/deflation loops at defined rate.
Interface delamination	Poor chemical/mechanical compatibility.	Multimaterial boundary and cure sequence.	Peel/shear/fatigue of printed interface.
Sensor drift	Conductive network rearrangement.	Strain localisation and wiring.	Cyclic electromechanical calibration.

Table 3. Common failure modes in VPP soft robots.

7. Multi-material integration

Combining rigid frames, soft chambers, responsive hydrogels and conductive elements can reduce assembly, but dissimilar networks may shrink differently, have different surface energies and carry different stresses during post-cure. The interface must therefore be treated as its own material. Bonding mode, print sequence, overlap geometry and cyclic interfacial strength should be reported. Multi-material printing capability does not by itself establish a durable robotic joint.

8. Minimum reporting framework

Block	Minimum information	Reason	Claim limit
Material state	Resin class, cure/post-cure, conditioning.	Defines constitutive response.	No transfer from uncured or dry state.
Mechanics	Large-strain tensile, relaxation/hysteresis as relevant.	Captures soft constitutive behaviour.	Hardness is not enough.
Actuator geometry	Chambers, walls, orientation and dimensions.	Geometry controls motion.	No universal pressure-angle map.
Stimulus	Pressure, temperature, fluid, voltage and rate.	Defines driving condition.	Response cannot be detached from stimulus.
Cycling	Cycle count, amplitude, frequency and failure criterion.	Establishes durability.	One cycle is feasibility only.
Interfaces	Materials, print sequence, bonding method.	Defines multimaterial reliability.	No durable-interface claim without testing.
Device output	Displacement, force, leak, sensor signal as appropriate.	Connects coupon to function.	Supports tested device configuration only.

Table 4. Minimum reporting set for VPP soft-robotics materials.

3Dresyns implementation examples

Several 3Dresyns materials illustrate different soft-robotics design axes without constituting evidence of actuator-level performance.

- Manufacturer documentation positions 3Dresyn Soft SR A30 and 3Dresyn Hard SR A70 as silicone-like compliance points for elastomeric printed structures. Hardness alone is not used here to predict bending, leakage or fatigue [M1,M2].
- Manufacturer documentation positions NextGen 3Dresyn SEA10 as a super-elastic grade. It is an implementation example for large-deformation material selection; actuator durability still requires cyclic device testing [M3].
- Manufacturer documentation positions 4Dresyn ETR35 Bio as an electro-thermo-responsive hydrogel platform. Its product identity does not establish actuation amplitude, response time or integrated robotic performance without a defined device and stimulus protocol [M4].

These products illustrate separate material routes - silicone-like elastomers, super-elastic networks and responsive hydrogels. Their suitability for a specific soft robot depends on geometry, process, environment, stimulus and validation.

9. Conclusions

- Soft-robot performance is a coupled material-geometry problem.

- Hardness and monotonic elongation are insufficient descriptors for pneumatic or cyclic actuation.
- Leakage, tear, hysteresis, creep and fatigue should be measured under device-relevant stimulus histories.
- Stimuli-responsive materials require kinetic as well as equilibrium characterisation.
- Multi-material interfaces are functional materials in their own right and require cyclic validation.
- Coupon data should support constitutive understanding, while actuator claims must be measured on the device.
- Commercial soft/responsive grades are implementation options, not evidence of universal actuator performance.

Limitations

The review does not compare bending angles or pressures numerically across studies because device geometries and actuation protocols are not standardised. Biomedical or skin-contact suitability is outside the evidence scope unless separately validated.

Author contributions

Juan Segurola: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests

The author is affiliated with 3Dresyns by Resyner Technologies S.L. Commercial 3Dresyns materials are identified only as implementation examples supported by controlled product documentation. They are not treated as independent peer-reviewed evidence and no proprietary formulation composition is disclosed.

Data availability

No new experimental dataset was generated for this review. Scientific statements are attributed to the cited literature and standards; commercial examples are separated from the independent evidence base.

Company information

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