DRAGONWORX BIOMIMETIC TECHNOLOGIES

Research Collaboration Proposal

From Gecko to Remora:

Synthesis, Characterization, and Cycle-Fatigue Testing of a Four-Mechanism Biomimetic Adhesion Stack

at Human Body-Weight Scale

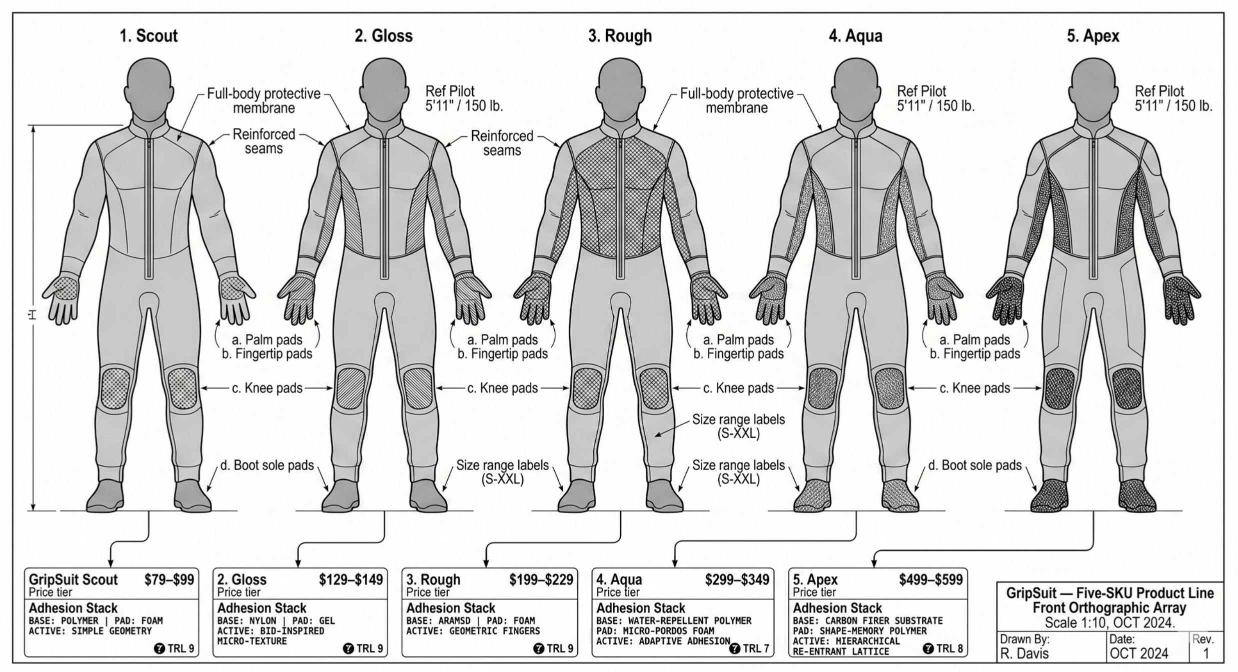

Figure 0.1 — GripSuit five-SKU product line, front orthographic array. Scale 1:10, reference pilot 5'11" / 150 lb. Left to right: Scout, Gloss, Rough, Aqua, Apex — each carrying a distinct adhesion stack matched to its primary surface class.

Submitted to:

Advanced Materials and Polymer Research Laboratories
Departments of Materials Science & Engineering and Mechanical Engineering

Shape-Memory Polymer, CNT Composite, and Biopolymer Research Groups

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Abstract

DragonWorx Biomimetic Technologies proposes a collaborative materials fabrication and characterization program with an advanced polymer and materials research laboratory to address four interlocking research gaps in the development of the GripSuit — a wearable biomimetic adhesion platform designed for human-scale dry, rough-surface, and submerged climbing across the full spectrum of real-world substrate classes.

The GripSuit architecture integrates four biological adhesion mechanisms in a zone-selective composite pad system: (1) hierarchical polyurethane nano-pillar arrays with 200 nm spatular tips replicating tokay gecko (Gekko gecko) setal geometry, targeting Van der Waals adhesion of 10 N/cm² on smooth surfaces (Ra < 25 µm); (2) Shore 20A silicone compliant disc lips with TPU micro-filament arrays derived from northern clingfish (Gobiesox maeandricus) disc architecture, enabling equal-performance adhesion across Ra 50–800 µm; (3) PDMS lamellar spinule arrays whose self-tightening geometry under shear load replicates the remora (Echeneis naucrates) disc mechanism, validated at 27 N on a 45 g bioinspired prototype; and (4) DOPA-catechol surface chemistry derived from mussel (Mytilus edulis) byssal thread bonding for submerged wet adhesion on steel and concrete.

Four research threads are proposed for the collaborative program, each aligned with established expertise in leading polymer-engineering research groups: (A) SMP-substrate compliance grading for pad backing geometry using thiol-ene/acrylate systems; (B) hierarchical PU + CNT composite nano-pillar fatigue characterization across 10,000+ attach-detach cycles at full body-weight loading; (C) PVDF harvesting power budget characterization for the electrostatic augmentation and self-cleaning circuits under simulated climb duty cycles; and (D) DOPA-mimetic polymer synthesis and submerged adhesion characterization for the Aqua SKU disc lip. Together these four threads close the primary technical gaps separating the current TRL 3–5 component technologies from an integrated, validated wearable platform. Each thread is specified with explicit attention to the methodological points a materials reviewer will demand: loading-mode realism (peel as well as shear), replicate count and Weibull statistics, CNT dispersion control, catechol oxidation control, spatial verification of property gradients, a first-order power budget stated before measurement, and a standardized adhesion metrology protocol (Section 7).

An IP co-development framework with joint patent rights on fabrication innovations is proposed. DragonWorx retains product commercialization rights; the research partner retains publication rights and co-inventor status on any novel polymer architectures arising from the collaboration. This document describes the technical basis, proposed experimental program, IP framework, and timeline for the partnership.

1. Introduction and Research Motivation

1.1 The Unsolved Surface Coverage Problem

The Van der Waals dry adhesion architecture validated by DARPA's Z-Man program in 2014 — a 100 kg climber ascending 7.6 m of vertical glass — established proof of concept for gecko-inspired wearable adhesion at human scale. That demonstration was extraordinary. It was also limited to smooth, dry, polarizable surfaces in a controlled environment. The building envelope of any real structure includes glass curtain wall, painted steel, raw concrete, masonry, and wet or submerged surfaces depending on the application. No single Van der Waals pillar geometry addresses this full matrix.

The surface compatibility collapse of gecko-style pillar arrays on rough substrates is not a fabrication failure — it is a geometry one. Pillar tips at 200 nm diameter and 5–10 µm height cannot bridge the asperity valleys of cast concrete (Ra 100–400 µm) or natural rock (Ra 200–800 µm). The tips contact only the asperity peaks, reducing effective contact area by 95% or more and reducing adhesion force proportionally. The solution requires not a better vdW pillar, but an additional mechanism operating at a different geometric scale — one that exploits rather than avoids surface roughness.

The GripSuit platform addresses this by stacking four biological mechanisms, each calibrated to a distinct roughness regime, in a zone-selective pad architecture. The biological models are not arbitrary — each represents a creature that solved the exact surface class problem in question, under evolutionary pressure from real physical loads over geological time.

1.2 The Right Research Partner Profile

The GripSuit research program is not primarily a fluid mechanics problem — it is a polymer synthesis, thermomechanics, and fabrication problem. Three of the four proposed research threads require exactly the expertise documented in the published literature of leading polymer-engineering and CNT-composite research groups:

Shape-memory polymer backing geometry. The GripSuit backing layer requires a spatially graded stiffness — compliant at the center to allow nano-pillar tip conformance, stiffer at the perimeter to resist peel initiation. Published thiol-ene/acrylate SMP systems, which have been demonstrated to soften in vivo from over 600 MPa to 6 MPa in implantable neural-interface applications, present a direct fabrication pathway for this compliance gradient through spatial variation of crosslink density or Tg within a single substrate layer.

CNT composite pillar longevity. Published work on carbon nanotube yarn artificial muscles has demonstrated more than one million actuation cycles from CNT composite polymer systems. The GripSuit's critical open gap — nano-pillar fatigue under repeated full-body-weight loading — maps directly onto this material characterization expertise. A PU + CNT composite pillar tip geometry that maintains adhesion across 10,000+ cycles would close the highest-priority development gap in the platform.

Energy harvesting integration. The GripSuit electrostatic augmentation and self-cleaning circuits draw from a body-motion PVDF harvesting network. The established literature on flexible PVDF energy-harvesting systems provides the characterization methodology for establishing whether the harvested power budget reliably drives the ES and cleaning circuits under realistic climb duty cycles — a question the current design leaves unanswered.

The fourth thread — DOPA-mimetic polymer synthesis for the Aqua SKU — falls within the biopolymer mechanics domain and would constitute new primary research with strong publication potential targeting the Journal of Materials Chemistry B or Biomacromolecules.

DragonWorx is based in the Dallas–Fort Worth metroplex and places strong value on geographic proximity to the research partner: co-located sample exchange, fabrication iteration, and design review proceed at the pace of a single institution rather than at the pace of interstate shipping and remote coordination. Proximity is a selection criterion, not a requirement.

2. The GripSuit Platform — Four Biological Mechanisms

The GripSuit adhesion stack integrates four biological mechanisms, each operating at a distinct surface roughness scale. The zone-selective pad architecture assigns each mechanism to the pad regions where it performs without interference from the others. Figure 2.1 illustrates the exploded zone cross-section of the Apex palm pad.

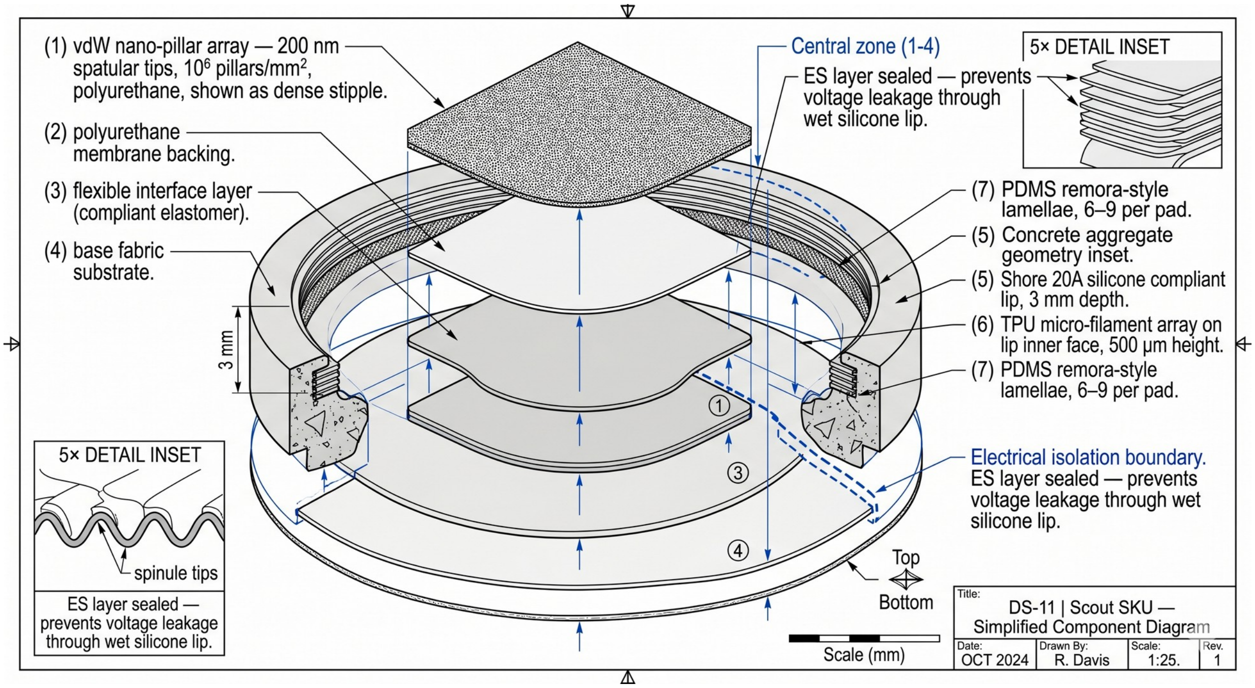


Figure 2.1 — GripSuit Apex palm pad, zone-selective exploded cross-section. Central zone (layers 1–4): vdW nano-pillar array, polyurethane membrane, flexible interface layer, base fabric. Annular zone: Shore 20A silicone compliant lip (3 mm depth), TPU micro-filament array (500 µm height), PDMS remora-style lamellae (6–9 per pad). Electrical isolation boundary between ES layer and silicone lip shown in dashed blue. 5× spinule tip detail inset lower-left.

2.1 Mechanism I — Gecko Van der Waals Nano-Pillar Array (TRL 5)

The primary adhesion mechanism for smooth surfaces replicates the hierarchical setal geometry of the tokay gecko (Gekko gecko). Polyurethane micro-pillars (5–10 µm height, 2–5 µm diameter) capped with 200 nm spatular tips at ~10^6 pillars/mm^2 engage Van der Waals forces at 5–10 nm contact separation. The anisotropic load dependence — high adhesion in shear (parallel to surface), low release force in peel (perpendicular) — allows directional detachment through wrist rotation without sustained muscular effort.

Validated adhesion: 10 N/cm^2 shear on smooth, dry, polarizable surfaces. DARPA Z-Man (2014) demonstrated full human body-weight support (100 kg climber plus 22 kg equipment) on vertical glass using a precursor architecture. The mechanism fails on surfaces with Ra > ~25 µm where asperity geometry excludes pillar tips from the majority of the contact area.

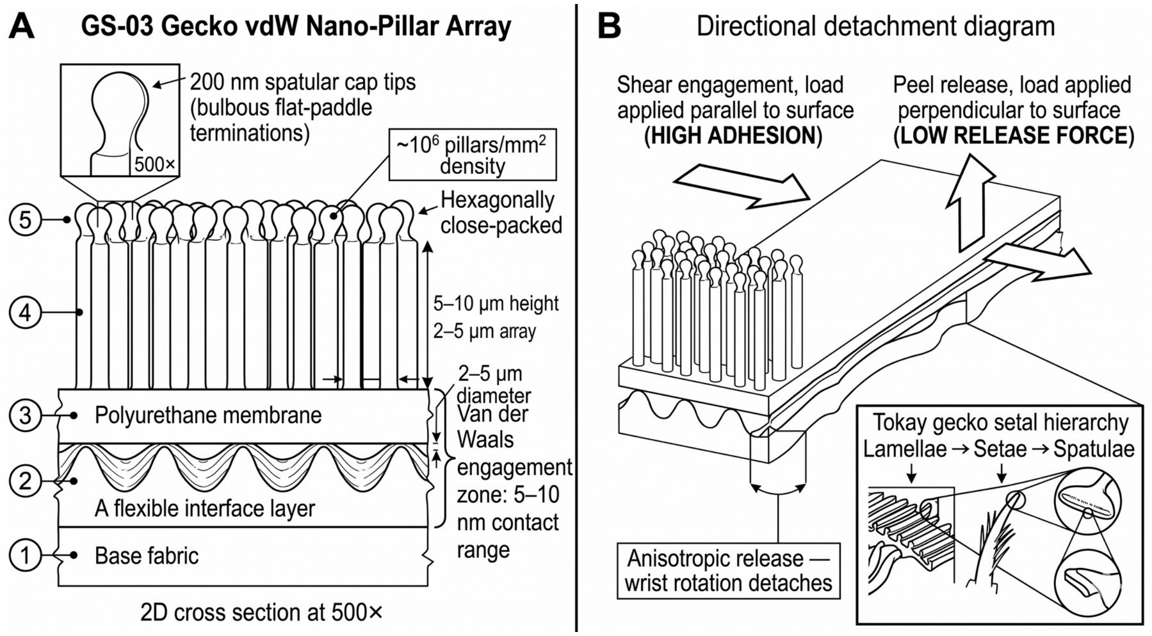


Figure 2.2 — GS-03: Gecko vdW nano-pillar array. Panel A: five-layer stack cross-section at 500× — base fabric, flexible interface layer, polyurethane membrane, pillar array (5–10 µm height, 2–5 µm diameter, hexagonally close-packed), 200 nm spatular tips. vdW engagement zone: 5–10 nm. Panel B: directional detachment diagram — shear engagement (high adhesion) vs. peel release (low force). Tokay gecko setal hierarchy inset (lamellae → setae → spatulae).

2.2 Mechanism II — Clingfish Compliant Disc Lip (TRL 3)

The northern clingfish (Gobiesox maeandricus) adheres to barnacle-encrusted, algae-fouled intertidal rock with equal tenacity across the full range of surface roughness encountered in the intertidal zone — the exact substrate regime where gecko vdW adhesion collapses. The disc architecture: a stiff central core surrounded by a highly compliant, flexible lip that deforms to conform to and seal around macro-scale aggregate geometry. Hierarchical micro-filaments at the disc edge engage surface asperities in shear.

In the GripSuit, this translates to a Shore 20A silicone annular lip (3 mm depth, 12 mm radial width) surrounding the central vdW pad zone at each palm and boot pad. On smooth glass the lip sits inert at the perimeter — no interference with vdW contact. On concrete (Ra 100–400 µm) or rock (Ra 200–800 µm), the aggregate engages the lip, the TPU micro-filament array (500 µm height) bites into asperity faces, and the two mechanisms operate in parallel.

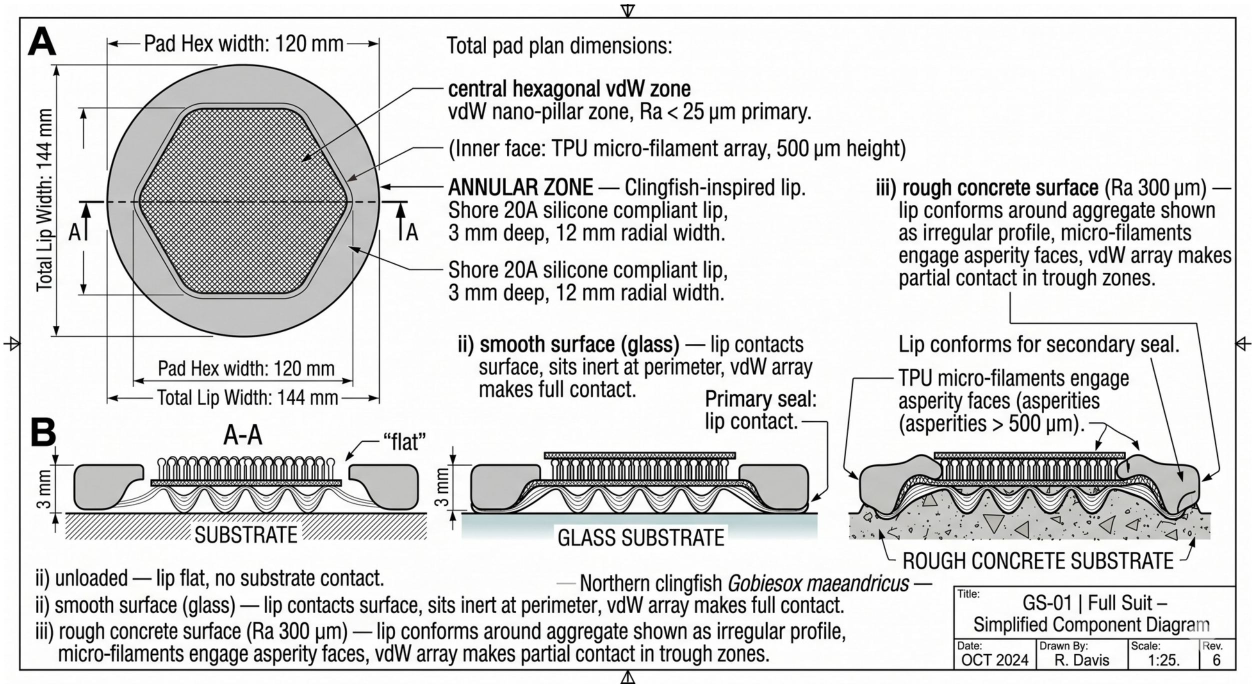


Figure 2.3 — GS-04: Clingfish compliant disc lip. Panel A: palm pad plan view — central hexagonal vdW zone (Ra < 25 µm primary) surrounded by Shore 20A silicone annular lip (3 mm deep, 12 mm radial width). Pad hex width 120 mm, total lip width 144 mm. Panel B: Section A-A in three substrate states — unloaded (lip flat, no contact); smooth glass (lip inert at perimeter, vdW full contact); rough concrete Ra 300 µm (lip conforms to aggregate, micro-filaments engage asperity faces). Biological model: Gobiesox maeandricus.

2.3 Mechanism III — Remora Lamellar Spinule Array (TRL 3)

The remora (Echeneis naucrates) evolved its adhesive disc to grip the rough skin of sharks while being dragged through water at speed — a self-tightening mechanism under the exact dynamic loading conditions a vertical climber generates when shifting body weight laterally. The disc interior carries linear lamellae bearing spinule tips oriented such that shear force passively rotates each lamella into greater spinule contact, increasing local friction coefficient proportionally with applied load. A 45 g bioinspired disc with 12 lamellae and 294 spinules withstood 27 N in published trials (Gamel et al. 2019).

In the GripSuit, PDMS lamellae with TPU spinule tips (6–9 per palm pad, 9 per knee pad) integrate into the inner face of the clingfish compliant lip. The mechanism activates under shear load and relaxes for repositioning, with no actuation required. The remora mechanism provides the primary load-bearing capability for the Aqua SKU in submerged conditions where neither vdW nor electrostatic augmentation functions.

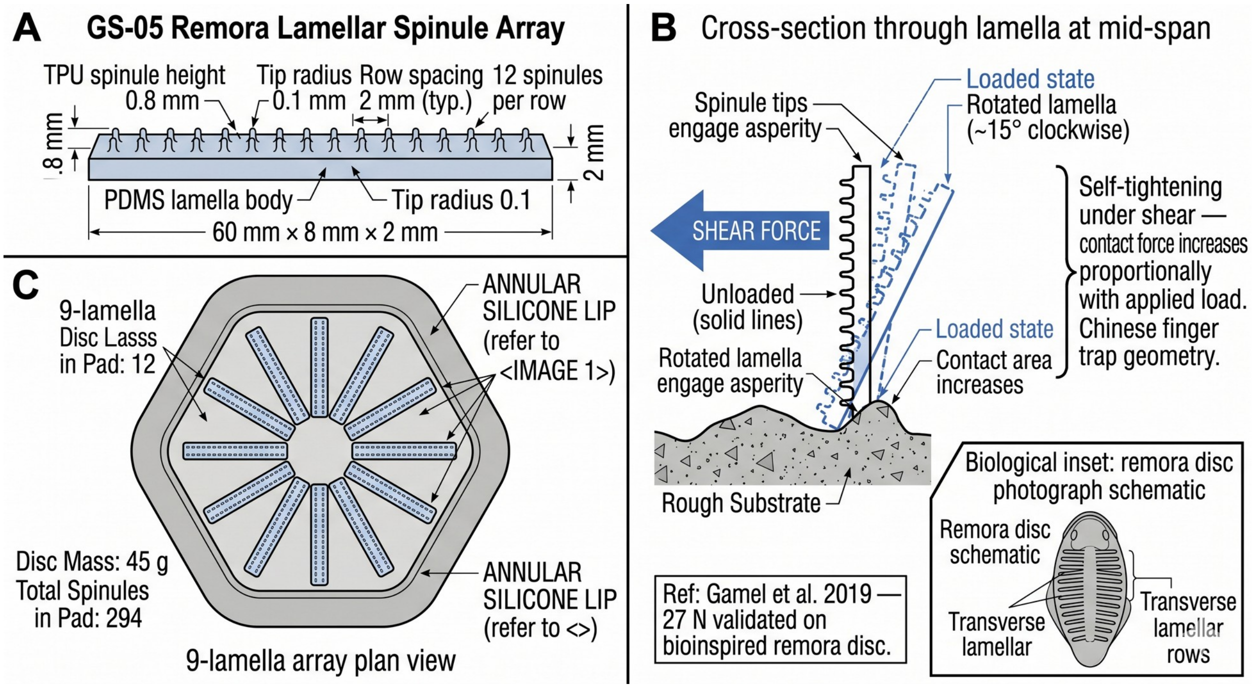


Figure 2.4 — GS-05: Remora lamellar spinule array. Panel A: single PDMS lamella (60 mm × 8 mm × 2 mm), TPU spinule tips (height 0.8 mm, tip radius 0.1 mm, row spacing 2 mm, 12 spinules/row). Panel B: cross-section at mid-span — unloaded state (lamella perpendicular, spinules not engaged) and loaded state (15° clockwise rotation under shear, spinule tips engaged in asperity, contact area increases). Self-tightening annotation: "Chinese finger trap geometry." Panel C: 9-lamella array plan view in annular lip, disc mass 45 g, 294 spinules total. Biological reference: Gamel et al. 2019.

2.4 Mechanism IV — DOPA-Mimetic Mussel Chemistry (TRL 2)

Mussels (Mytilus edulis) achieve ~0.4 MPa bonding to wet rock, steel, and biological surfaces through 3,4-dihydroxy-L-phenylalanine (DOPA) — a modified amino acid forming coordinate bonds with metal oxides (Fe^{3+}, Ti^{4+}) and hydrogen bonds with hydroxyl-bearing surfaces, even fully submerged. DOPA-catechol chemistry at the byssal thread tip displaces water from the interface through a combination of covalent cross-linking and surface bridging unavailable to physical adhesion mechanisms.

For the GripSuit Aqua SKU, a DOPA-mimetic polymer coating on the silicone disc lip surface augments the remora spinule mechanism in fully submerged conditions. No electronics, no PVDF harvesting, no power draw — entirely passive wet-chemistry bonding. Synthesis and submerged adhesion characterization of this layer constitute the primary research frontier of the proposed collaboration.

2.5 Zone-Selective Pad Architecture and Electrical Isolation

The three physically compatible mechanisms (vdW, clingfish lip, remora lamellae) operate in concentric zones within each pad — central vdW zone surrounded by the annular clingfish-remora lip zone. The electrostatic augmentation layer for the Gloss and Apex SKUs operates within the central zone only, sealed from the silicone lip by an electrical isolation boundary. This prevents voltage leakage (1–3 kV) through moisture in the silicone-concrete interface — a packaging constraint documented in the GripSuit engineering record and requiring confirmation through the proposed PVDF thread.

2.6 Surface Roughness Compatibility by SKU

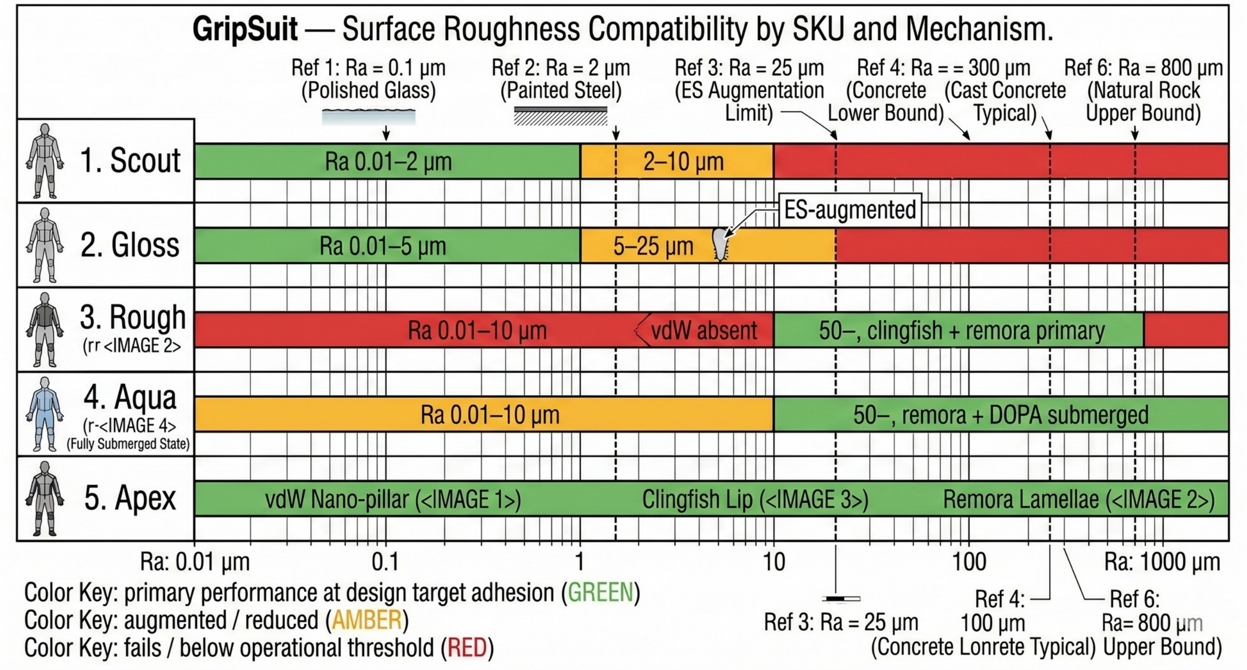


Figure 2.5 — GS-07: Surface roughness compatibility map. Horizontal axis: Ra (µm), logarithmic, 0.01–1,000 µm. Five GripSuit SKUs as horizontal bands. Green: primary mechanism at design target. Amber: augmented/reduced performance. Red: fails/below threshold. Reference lines at Ra = 0.1 µm (polished glass), 2 µm (painted steel), 25 µm (ES augmentation limit), 100 µm (concrete lower bound), 300 µm (cast concrete typical), 800 µm (natural rock upper bound).

3. Proposed Research Program — Four Threads

The four research threads are independent but interact. Thread A produces the substrate upon which Threads B and C operate. Thread D runs in parallel as a self-contained synthesis program. All four produce primary data suitable for peer-reviewed publication.

3.1 Thread A — SMP Compliance-Graded Backing Substrate

Research Question

Can a thiol-ene/acrylate shape-memory polymer substrate be spatially programmed with a compliance gradient — high modulus ($E > 500$ MPa, glassy state) at the pad perimeter and low modulus ($E < 2$ MPa, rubbery state) at the center — such that it simultaneously resists edge-peel initiation and permits spatular tip conformance to substrate waviness under full body-weight loading?

Technical Approach

The Geckskin draping backing architecture (Bartlett et al. 2012) demonstrated that a compliant draping layer substantially increases macroscale adhesion by distributing peel-initiation stress across the pad perimeter rather than concentrating it at the edge. Established thiol-ene/acrylate SMP systems offer a direct fabrication pathway: spatial variation of crosslinker density during photolithographic patterning can produce a backing layer with a programmed radial Tg gradient. Above Tg the material is compliant (permits conformance); below Tg it is glassy (resists peel).

A single backing disc of 120 mm diameter would be patterned with: central zone (60 mm diameter) Tg near 37°C — body-temperature-activated compliance for tip conformance; perimeter annulus (60–120 mm) Tg significantly above 37°C — remains in glassy, peel-resistant state at all operational temperatures. The spatial patterning would be achieved through masked UV exposure varying crosslink density in concentric annular zones.

Experimental Milestones

Gradient Feasibility and Spatial Verification

The reviewer’s first question on this thread is whether a sharp radial Tg gradient survives fabrication: unreacted monomer diffuses across a crosslink-density boundary during cure and blurs the intended step. We treat gradient sharpness as a measured outcome, not an assumption. Bulk DMA alone is insufficient because it averages over the disc; instead the as-cured modulus field is mapped spatially by nanoindentation across the radial coordinate, resolving the actual achieved gradient and its transition width. If diffusion blurs the boundary beyond a usable width, two mitigations are tested: a staged cure that vitrifies each zone before the adjacent zone is exposed, and a discrete multi-material (co-molded) boundary in place of a continuous gradient.

Experimental Milestones

- Synthesize thiol-ene/acrylate backing discs with 3–5 radial Tg gradient steps; characterize bulk thermomechanical properties by DMA across 20–50°C and map the spatial modulus field by nanoindentation to quantify achieved gradient sharpness
- Measure peel-initiation force as a function of perimeter modulus using a custom peel-arm fixture at 90° and 180° peel angles on glass substrate
- Measure nano-pillar array adhesion (shear force) as a function of central zone compliance — confirm that lower central modulus improves tip contact area under 90 kg loading
- Identify optimal radial Tg profile; fabricate 5 backing discs for use in Thread B cycle testing

Expected Outcome and Publication Target

A spatially programmed SMP backing geometry with quantified peel-resistance and tip-conformance tradeoff data. Publication target: Advanced Functional Materials or ACS Applied Materials & Interfaces.

3.2 Thread B — PU + CNT Composite Pillar Fatigue Characterization

Research Question

What is the adhesion retention curve — adhesion force as a function of attach-detach cycle count — for hierarchical polyurethane nano-pillar arrays with varying concentrations of multi-walled carbon nanotube (MWCNT) tip reinforcement under 90 kg body-weight shear loading, and at what cycle count does adhesion fall below the operational threshold (SF 3.0 at 10 N/cm²)?

Technical Basis

The current GripSuit documentation explicitly flags pillar cycle longevity as the highest-priority open development gap. Early PDMS and CNT pillar arrays in the literature lost adhesion through pillar clumping, bending, and fracture within hundreds of cycles — far short of operational requirements for a commercial climbing platform. Published CNT yarn muscle work demonstrated > 10^6 mechanical cycles from a CNT composite polymer, suggesting that CNT reinforcement of the pillar tip geometry is the correct direction, but the fatigue behavior of CNT-reinforced PU spatular tips under human-scale loading has not been characterized.

Loading Mode: Why Shear Alone Is Insufficient

A materials reviewer will immediately note that gecko-style adhesives carry load in shear but fail in peel. Field detachment of a climbing pad is almost always peel- or cleavage-initiated at a pad edge, not a uniform shear overload. A fatigue protocol that cycles only in pure shear would therefore characterize the wrong failure mode and overstate durability. The Thread B protocol consequently cycles in two regimes: (i) shear-dominant loading representing steady hang, and (ii) a peel-initiation regime in which a controlled normal/moment component is superimposed to reproduce the edge-cleavage condition that governs real detachment. Adhesion retention is reported separately for each regime, and the SEM failure-mode census distinguishes shear-driven tip fracture from peel-driven edge delamination.

Statistical Design

Adhesion of fibrillar arrays is stochastic: tip-to-substrate contact fraction varies with preload, dwell, and local defect population, so single-coupon measurements are not interpretable. Each condition (MWCNT concentration × substrate × loading regime) is tested with a minimum of $n = 5$ independent coupons, with adhesion strength fit to a two-parameter Weibull distribution to capture the characteristic strength and the scatter (Weibull modulus) that predicts the weakest-link behavior relevant to a safety-critical wearable. All retention curves are reported with 95% confidence intervals, and a power analysis during scoping will confirm whether $n = 5$ resolves the expected effect size between concentrations or whether replicate count must increase.

CNT Dispersion Control and Handling

MWCNT composite properties are dominated by dispersion quality; agglomeration is the usual cause of property scatter and premature fracture. Dispersion will be characterized by optical and electron microscopy and, where informative, by dynamic light scattering of the precursor suspension, and reported alongside each mechanical result so that fatigue differences are attributable to concentration rather than to uncontrolled agglomeration. Dry MWCNT powder presents a respirable-fiber inhalation hazard; all handling follows the host institution's nanomaterial EHS protocol (enclosed handling, HEPA filtration, fixed-substrate processing after dispersion), documented in the project safety plan before fabrication begins.

Adhesion Metrology Standard

All adhesion measurements use a fixed, reported protocol: defined preload, controlled dwell time, and controlled detachment rate, with shear measurements referenced to ASTM D3163-style lap-shear geometry and normal/peel measurements to a defined peel-arm fixture. Because gecko-class adhesion is strongly preload- and dwell-dependent, preload and dwell are held constant within a campaign and varied deliberately in a dedicated sub-study so that the reported retention curves correspond to a single, stated contact condition rather than an uncontrolled one.

Experimental Milestones

- Fabricate pillar arrays (5–10 µm height, 2–5 µm diameter, 200 nm spatular tips) in four MWCNT concentrations: 0%, 0.5%, 1.0%, 2.0% by mass in polyurethane matrix; characterize dispersion for each batch
- Mount arrays on Thread A SMP backing discs; characterize baseline adhesion (shear force at 90 kg loading) on smooth glass and polished granite by lap-shear test
- Run attach-detach fatigue protocol in both shear and peel-initiation regimes: 1, 10, 100, 500, 1,000, 5,000, 10,000 cycles; n = 5 per checkpoint; the 10,000-cycle target derives from a duty-cycle model of roughly 2,000–3,000 hand/foot placements per multi-pitch ascent across multiple service cycles, justified in the scoping memo
- Characterize failure modes by SEM at each checkpoint: pillar clumping, tip fracture, delamination from backing
- Identify MWCNT concentration at which 10,000-cycle retention exceeds 80% of baseline in the governing (peel) regime, reported with Weibull characteristic strength and modulus

Expected Outcome and Publication Target

A CNT concentration–cycle fatigue matrix for hierarchical PU spatular tip arrays — the first published dataset for this geometry at human body-weight loading. Publication target: ACS Nano or Soft Matter.

3.3 Thread C — PVDF Harvesting Power Budget for ES Augmentation and Self-Cleaning

Research Question

Does the harvestable piezoelectric power from PVDF films integrated into the GripSuit boot-sole and palm pad repositioning motions during a simulated 10 m glass-surface climb reliably supply the charge required to: (a) drive the electrostatic augmentation layer at 1–3 kV for continuous adhesion augmentation on Ra 5–25 µm surfaces, and (b) execute a four-second self-cleaning cycle between each repositioning event?

Technical Approach

The electrostatic augmentation layer (interdigitated electrode grid, dielectric elastomer substrate) requires a charge supply that scales with electrode area and applied voltage. The self-cleaning circuit requires a brief high-voltage burst at 1–5 Hz square wave. Both draw from a PVDF harvesting network embedded in the boot-sole flex zones and wrist joints — areas that undergo repeated bending and extension during a climb. The power budget depends on the product of harvested charge per motion cycle and the motion frequency, minus the charge consumed per ES and cleaning event.

A PVDF-MWCNT composite film (produced by standard electrospinning) targeting the crystalline β-phase for maximum piezoelectric coefficient would be integrated into a simulated boot-sole flex fixture cycling at 1 Hz (representative climb step rate). Output voltage, current, and charge per cycle would be measured across a range of pad areas and flex amplitudes. Comparison against ES and cleaning circuit charge requirements would validate or refute the self-powered design assumption.

First-Order Power Budget — Stated Before Measurement

A reviewer will want the order-of-magnitude balance before committing equipment time, so we state it explicitly. Electrostatic adhesion stores energy $E = \frac{1}{2} C V^2$ in the pad capacitance. For an 80 cm^2 interdigitated electrode pad, the effective capacitance is on the order of 1–10 nF; at 2 kV this corresponds to roughly 2–20 mJ of stored energy per pad per engagement. A self-cleaning burst re-cycles a comparable energy several times. Piezoelectric harvesting from a flexing PVDF boot-sole insert realistically yields on the order of tens to a few hundred microjoules per step at 1 Hz. The honest implication is that continuous high-voltage ES augmentation is unlikely to close on harvested power alone, whereas an intermittent, charge-recycling duty cycle (engage, hold electrostatically with leakage-limited top-up, release) may close. Thread C therefore tests a specific hypothesis — that an intermittent top-up duty cycle, not continuous drive, is what the harvested budget can sustain — and reports the measured margin or deficit rather than presuming success. A small supervisory buffer (supercapacitor) is included as the realistic architecture if pure harvesting falls short.

Dielectric Safety and Leakage

Operating a wearable at 1–3 kV raises dielectric breakdown, leakage, and operator-safety questions that must be addressed for any human-worn prototype. The program characterizes dielectric breakdown margin of the electrode encapsulation, leakage current in humid and wet conditions (directly relevant given the silicone-lip isolation boundary), and fault behavior. No human-worn testing of an energized system occurs until breakdown margin and leakage are characterized on the bench and a current-limiting fault architecture is validated.

Experimental Milestones

- Fabricate PVDF-MWCNT electrospun films at 0%, 0.5%, 1.0% MWCNT; characterize d33 piezoelectric coefficient and crystalline β-phase fraction by FTIR and XRD
- Integrate films into boot-sole flex fixture; measure harvested charge per cycle at 0.5, 1.0, 1.5 Hz flex rate over 100-cycle runs
- Characterize ES electrode layer charge consumption at 1 kV, 2 kV, and 3 kV for 80 cm^2 palm pad area
- Characterize self-cleaning circuit charge consumption: four-second 1–5 Hz burst, 2 kV, full palm pad area
- Determine power balance for an intermittent top-up duty cycle (not continuous drive): does harvested charge per step plus supervisory buffer sustain ES hold and periodic self-clean?
- Characterize electrode encapsulation dielectric breakdown margin and leakage current in dry, humid, and wet conditions; validate current-limiting fault architecture before any energized wear test

Expected Outcome

A validated (or refuted) self-powered design assumption for the GripSuit electrostatic subsystem, with a quantified PVDF film specification. If the power balance closes, this constitutes a self-powered wearable adhesion augmentation system — publishable in npj Flexible Electronics or Advanced Energy Materials.

3.4 Thread D — DOPA-Mimetic Polymer Synthesis for Aqua SKU (Submerged Wet Adhesion)

Research Question

Can a DOPA-catechol functionalized silicone surface coating on the Shore 20A disc lip produce quantifiable shear adhesion to submerged cast concrete (Ra 100–400 µm) and mild steel (Ra 2–8 µm) surfaces that meaningfully augments the remora lamellar mechanism, and how does adhesion retention vary with substrate iron-oxide content, submersion duration, and catechol oxidation state?

Technical Basis

Mussel adhesion through DOPA chemistry (Lee, Dellatore & Miller 2007; Waite & Tanzer 1981) achieves ~0.4 MPa on wet steel through a combination of Fe^{3+} coordinate bonding and H-bonding to surface hydroxyl groups. The catechol oxidation state is critical: reduced catechol bonds strongly; oxidized quinone cross-links but loses substrate affinity. A DOPA-mimetic coating that maintains reduced catechol in the submerged operating environment — without the lipid protection mechanism available to mussels in vivo — is the primary synthesis challenge.

Candidate coating architectures include: (a) polydopamine (PDA) thin-film deposition on the silicone lip surface; (b) catechol-functionalized PEG-silane grafted onto silicone hydroxyl groups; (c) mussel-inspired polypeptide brush coating. All three have precedent in the literature; none has been characterized on a compliant silicone substrate under shear loading against concrete roughness geometry.

Experimental Milestones

Catechol Oxidation Control — The Governing Difficulty

The dominant failure mode for DOPA-mimetic adhesion is catechol oxidation to quinone, which cross-links the coating but destroys substrate affinity. The proposal does not hand-wave this: oxidation state is controlled and tracked at every stage. Synthesis and cure are conducted under inert (N_2 or Ar) atmosphere at controlled acidic pH, which thermodynamically favors the reduced catechol; an antioxidant additive is screened as a second lever. Coatings are stored and shipped under inert conditions, and oxidation state is verified by UV-Vis (the ~395 nm quinone band) immediately before each adhesion test so that every adhesion datum is tagged with its measured oxidation state rather than an assumed one. The deliverable explicitly includes the adhesion-vs-oxidation-state relationship, since that curve determines achievable shelf life and operating window.

Experimental Milestones

- Synthesize three DOPA-mimetic coating architectures under inert atmosphere and controlled pH on 60 mm diameter Shore 20A silicone disc samples; characterize coating thickness, catechol surface density, and oxidation state by XPS and contact angle goniometry
- Measure submerged lap-shear adhesion against smooth steel, roughened steel (Ra 5 µm), and cast concrete (Ra 200 µm) after 1, 10, and 60 minutes submersion in fresh water and 3.5% NaCl solution

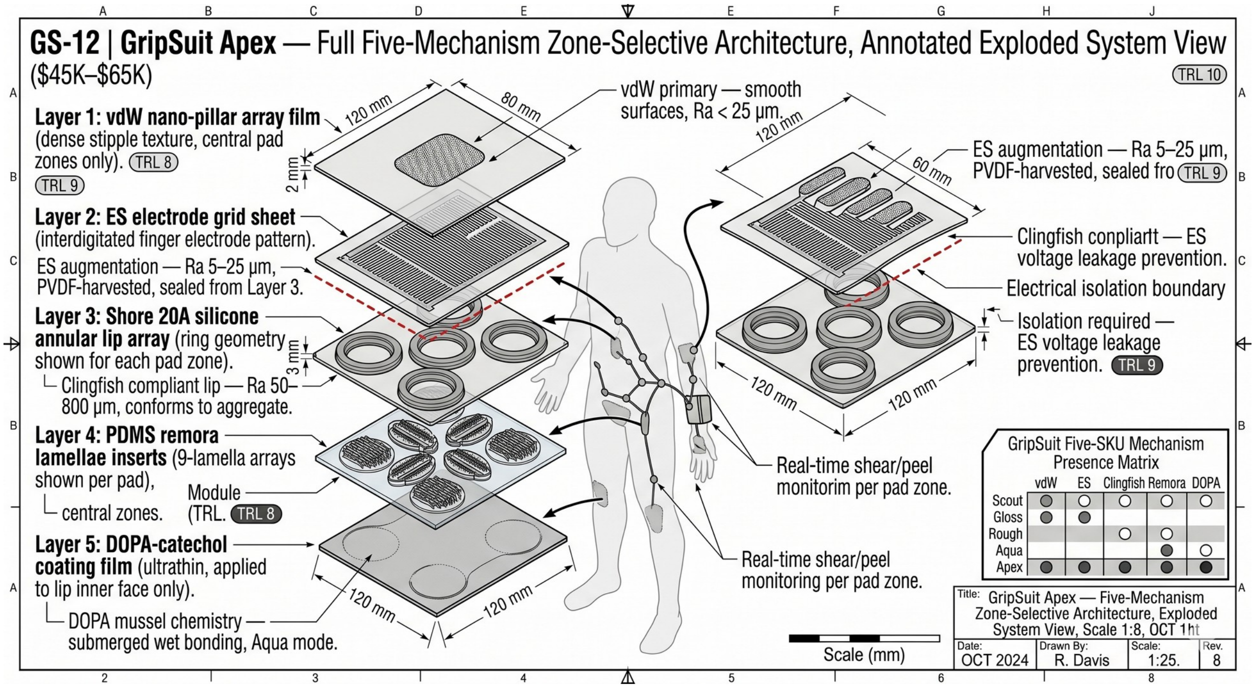
- Measure adhesion retention after 100 contact-release cycles in fresh water (quantify coating wear)
- Characterize catechol oxidation state after submersion by UV-Vis spectroscopy; correlate with adhesion retention
- Identify optimal coating architecture and identify substrate-specific performance limits

Expected Outcome and Publication Target

A quantified performance characterization of DOPA-mimetic coatings on compliant silicone against concrete and steel in submerged conditions — the first such dataset for a wearable-scale compliant disc geometry. Publication target: Journal of Materials Chemistry B or Biomacromolecules. DARPA Ocean Sciences and ONR programme offices represent potential co-funding pathways given the maritime infrastructure application.

4. Product Platform and Commercial Context

The four research threads directly underpin a five-SKU commercial product line. Each SKU carries the adhesion mechanisms appropriate to its target surface class; the research program validates the individual mechanism technologies before integration. Figure 4.1 presents the full Apex exploded system view showing all five mechanism layers in zone-selective configuration.



GripSuit Five-SKU Mechanism Presence Matrix

	vdW	ES	Clingfish	Remora	DOPA
Scout	●	○	○	○	○
Gloss	●	●			
Rough			○	○	
Aqua				●	○
Apex	●	●	●	●	●

Figure 4.1 — GS-12: GripSuit Apex — five-mechanism zone-selective architecture, exploded system view. Layer 1: vdW nano-pillar array film (central zones). Layer 2: ES electrode grid sheet (PVDF-harvested, sealed from Layer 3). Layer 3: Shore 20A silicone annular lip array (clingfish, Ra 50–800 µm). Layer 4: PDMS remora lamellae inserts (9-lamella arrays per pad). Layer 5: DOPA-catechol coating film (lip inner face, Aqua mode). Load sensor trace network to wrist module shown. Five-SKU mechanism presence matrix lower right. Scale 1:8.

SKU	Est. Price	Active Mechanisms	Primary Surfaces	Target Market	TRL (integrated)
GripSuit Scout	$349–$499	vdW nano-pillar (passive)	Glass, polished stone, CFRP, painted metal (Ra < 10 µm)	Consumer recreation, sport climbing training, STEM demonstration	TRL 4
GripSuit Gloss	$8K–$14K	vdW + ES hybrid + self-cleaning	Glass curtain wall, polished granite, painted steel, anodized aluminium (Ra < 25 µm)	High-rise façade access, building inspection, window cleaning contractors	TRL 4
GripSuit Rough	$6K–$38K	Clingfish compliant lip + remora lamellae	Rough concrete, masonry, brick, natural rock (Ra 50–800 µm)	Competitive climbing, structural inspection, SOF tactical urban operations	TRL 3

GripSuit Aqua	\$28K–\$55K	Remora lamellae + DOPA mussel chemistry · no electronics	Submerged concrete, steel pier, biofouled hull, wet rock	Maritime inspection, ship hull access, defence diving, dam inspection	TRL 2–3
GripSuit Apex	\$45K–\$65K	All five mechanisms, zone-selective	Full surface matrix — Ra < 0.1 µm through Ra 1,000 µm, dry through submerged	Special operations, urban SAR, extreme alpinism, defence procurement	TRL 3

The total addressable market for the SKUs most directly supported by the proposed research threads (Gloss: high-rise façade access; Rough: tactical/climbing; Aqua: maritime/defence) represents a combined opportunity exceeding \$3B at current market size across industrial rope-access replacement, tactical SOF equipment, and maritime infrastructure services. The Scout SKU targets the \$691M (2024) and growing recreational climbing equipment market as the proof-of-concept consumer entry point.

5. Intellectual Property Framework

DragonWorx raises this framework at the outset because any experienced principal investigator will have navigated IP co-development across university licensing agreements and, frequently, startup formation. We have no interest in an arrangement that creates ambiguity about ownership or incentive misalignment between publication and commercialization. The proposed structure is explicit by design.

Proposed IP Structure — Summary

DragonWorx retains exclusive product commercialization rights for the GripSuit platform and all derivative wearable products. The research partner retains co-inventor status and joint patent rights on any novel polymer fabrication methods, composite architectures, or synthesis protocols developed during the collaboration that constitute patentable inventions independent of the GripSuit application. The research partner retains full and unrestricted publication rights on all research findings with no publication delay beyond standard IP review (30-day review period). DragonWorx contributes the design specifications, biological mechanism documentation, and application engineering; the partner contributes fabrication infrastructure, characterization equipment, and graduate student effort. Funding for consumables, equipment time, and graduate student stipend contribution is proposed on a 60/40 basis (DragonWorx/partner institution), with formal structure subject to the host institution's Office of Research negotiation.

5.1 Ownership Categories by Thread

Thread	IP Category	Ownership Proposed	Publication Rights
A — SMP backing gradient	Novel SMP spatial patterning method	Joint patent — DragonWorx + host institution	Partner unrestricted
B — PU + CNT pillar fatigue	CNT composite PU pillar geometry and process	Joint patent — DragonWorx + host institution	Partner unrestricted
C — PVDF power budget	PVDF-MWCNT composite film specification	Joint patent if novel film architecture; otherwise DragonWorx	Partner unrestricted
D — DOPA coating synthesis	DOPA-mimetic coating chemistry and process	Joint patent — DragonWorx + host institution	Partner unrestricted
GripSuit product design	Suit architecture, zone-selective pad geometry, SKU definitions	DragonWorx sole ownership	N/A — commercial IP

5.2 Existing IP Landscape

The gecko-inspired dry adhesion space has a well-mapped patent landscape. Key reference patents include: Sitti & Fearing (2003, CMU) on micro-fibrillar adhesive structures; Bartlett et al. (2012, UMass) on the Geckskin draping backing architecture (US8703032B2); and multiple Draper Laboratory patents from the Z-Man program covering wearable gecko adhesion systems for climbing. The clingfish, remora lamellar, and DOPA-mimetic coating architectures applied to a wearable climbing system in the zone-selective configuration described here have not, to DragonWorx's knowledge, been claimed in issued patents — representing the primary whitespace for joint IP generation.

DragonWorx will provide a full prior art search report on all four mechanism areas as part of pre-collaboration scoping. We recommend conducting this jointly with the host institution’s technology transfer office before any fabrication work begins.

6. Experimental Program Summary

6.1 Test Matrix

Thread	Sample Type	Primary Measurement	Target Instrument	Cycles / Conditions
A — SMP backing	Thiol-ene/acrylate discs, 120 mm diam., 3–5 Tg gradient steps	Peel-initiation force; nano-pillar shear adhesion vs. central compliance	DMA, custom peel-arm fixture, lap-shear frame (90 kg)	3 peel angles × 5 Tg profiles = 15 conditions
B — PU+CNT pillar	4 MWCNT concentrations × 3 substrate classes = 12 sample sets	Adhesion force retention vs. cycle count (0–10,000 cycles)	Lap-shear frame, SEM at checkpoints	8 checkpoints per sample set
C — PVDF harvesting	PVDF-MWCNT films, 3 concentrations, boot-sole flex fixture	Harvested charge per cycle; ES and cleaning charge consumption	Lock-in amplifier, charge amplifier, Keithley source-measure unit	100-cycle characterization runs at 3 flex frequencies
D — DOPA coating	3 coating architectures × 3 substrate classes × 2 salinities = 18 conditions	Submerged lap-shear adhesion at 1, 10, 60 min; 100-cycle retention	Lap-shear frame, XPS, UV-Vis, contact angle	Submersion duration and salinity matrix

6.2 Deliverables

1. Thread A: SMP backing compliance gradient — fabrication protocol, thermomechanical characterization data, peel-resistance vs. compliance tradeoff curves, 5 backing discs for Thread B integration.
2. Thread B: PU + CNT pillar fatigue matrix — adhesion retention curves (0–10,000 cycles) for 4 MWCNT concentrations on 3 substrate classes; SEM failure mode characterization; identified operational longevity specification.
3. Thread C: PVDF power budget assessment — d33 characterization data for 3 PVDF-MWCNT compositions; harvested charge per cycle vs. flex rate; validated or refuted self-powered design assumption; if validated, PVDF film specification for GripSuit integration.
4. Thread D: DOPA coating performance — submerged shear adhesion data for 3 coating architectures vs. steel and concrete; oxidation state characterization; cycle retention data; optimal coating architecture recommendation.
5. Four peer-reviewed manuscript submissions targeting journals listed in Section 3 — co-authored by DragonWorx and partner-institution investigators.
6. A joint prior art analysis and provisional patent application on any novel fabrication architectures identified during the program.

6.3 Program Timeline

Phase	Duration	Threads Active	Milestone
Phase 0 — Scoping	2 months	All (pre-lab)	Prior art search complete; IP framework executed; research agreement signed; consumables ordered

Phase 1 — Fabrication	3 months	A, B (setup), D (synthesis)	SMP backing discs characterized; MWCNT pillar arrays fabricated; DOPA coating architectures synthesized and characterized
Phase 2 — Characterization	4 months	A (complete), B (running), C, D	Thread A deliverables complete; Thread B fatigue testing running; PVDF characterization; DOPA submerged testing
Phase 3 — Integration and Analysis	3 months	B (complete), C, D (complete)	Thread B complete; Thread C power balance determination; Thread D complete; data analysis across all threads
Phase 4 — Publications and IP	4 months	All (writing)	Manuscript submissions; provisional patent application(s); DragonWorx design iteration based on findings

7. Anticipated Technical Questions and Risk Register

Written in the reviewer’s voice. These are the objections a polymer and materials scientist should raise on first reading, with our planned response. We prefer to surface them ourselves.

7.1 "Your fatigue test loads in shear, but these adhesives fail in peel."

Correct, and now addressed in Thread B. The fatigue protocol cycles in both a shear-dominant regime and a peel-initiation regime that superimposes the normal/moment component governing real edge-cleavage detachment. Retention is reported separately for each, and failure-mode census distinguishes the two. The governing (peel) regime sets the operational longevity claim.

7.2 "Single coupons tell you nothing — where is the statistics?"

Each condition uses $n \geq 5$ independent coupons with two-parameter Weibull fitting to capture characteristic strength and scatter, and all curves carry 95% confidence intervals. A scoping-phase power analysis confirms whether $n = 5$ resolves the inter-condition effect size or whether replicate count must rise. Adhesion is treated as the stochastic, weakest-link quantity it is.

7.3 "MWCNT properties live or die on dispersion — how is it controlled?"

Dispersion is characterized for every batch (microscopy; DLS of precursor suspension where informative) and reported alongside each mechanical result, so fatigue differences are attributable to concentration rather than agglomeration. Respirable-fiber handling follows the host institution’s nanomaterial EHS protocol, documented before fabrication.

7.4 "Catechol oxidizes — your DOPA coating will be dead on arrival."

This is the governing difficulty for Thread D and is controlled explicitly: inert-atmosphere, controlled-pH synthesis and cure; antioxidant screening; inert storage; and UV-Vis verification of oxidation state immediately before every adhesion test, so each datum is tagged with measured oxidation state. The adhesion-versus-oxidation-state curve is itself a deliverable.

7.5 "Can a sharp Tg gradient actually be fabricated in one disc?"

Treated as a measured outcome in Thread A. The achieved modulus field is mapped by nanoindentation (not inferred from bulk DMA), and if monomer diffusion blurs the boundary beyond a usable width, a staged vitrifying cure or a discrete co-molded boundary is tested as fallback.

7.6 "Does the harvested power actually close the electrostatic budget?"

We state the order-of-magnitude balance up front in Thread C rather than presuming it: stored pad energy is on the order of millijoules per engagement while per-step harvesting is tens to hundreds of microjoules, so continuous drive is unlikely to close and an intermittent charge-recycling top-up duty cycle with a small supervisory supercapacitor is the hypothesis under test. The program reports the measured margin or deficit, not an assumed success.

7.7 "A 1–3 kV wearable raises safety questions."

Addressed in Thread C. Dielectric breakdown margin, humid/wet leakage, and fault behavior are characterized on the bench, and no energized human-worn test occurs until a current-limiting fault architecture is validated. Any eventual human wear-testing proceeds only under the host institution’s human-subjects review.

7.8 "What is your adhesion measurement protocol?"

A fixed, reported protocol with defined preload, dwell, and detachment rate, referenced to ASTM D3163-style lap shear for shear and a defined peel-arm fixture for peel. Because gecko-class adhesion is strongly preload- and dwell-dependent, those variables are held constant within a campaign and varied only in a dedicated sub-study.

7.9 "Your fatigue substrate is clean lab glass; the field is filthy."

Acknowledged. The baseline fatigue campaign uses controlled substrates for interpretability; a dedicated contamination sub-study introduces representative particulate fouling and evaluates the electrostatic self-cleaning recovery against it. We do not claim clean-substrate longevity transfers to fouled field conditions without that sub-study.

8. Technology Readiness and Advancement Through Collaboration

Technology	Current TRL	Limiting Factor	Proposed Thread	TRL After Program
vdW PU nano-pillar array	TRL 5	Cycle fatigue at body-weight loading uncharacterized; backing compliance not optimized	A + B	TRL 6
SMP compliance-graded backing	TRL 3	Spatial Tg patterning in disc geometry not demonstrated	A	TRL 5
ES augmentation + self-cleaning	TRL 4	PVDF power budget vs. circuit requirements unvalidated	C	TRL 5
Clingfish compliant silicone lip	TRL 3	Fabrication at wearable scale; integration with vdW central zone not tested	A + B (substrate)	TRL 4
Remora PDMS lamellae	TRL 3	Shear fatigue at body-weight loading uncharacterized	B (comparative)	TRL 4
DOPA-mimetic mussel coating	TRL 2	Coating synthesis and submerged characterization on compliant silicone not attempted	D	TRL 4
Integrated Apex pad system	TRL 3	No integrated test of all mechanisms in zone-selective configuration	A + B integration	TRL 4–5

The proposed 16-month program advances the integrated GripSuit platform from TRL 3 (individual component technologies validated in laboratory) to TRL 4–5 (technology validated in relevant environment at component and sub-system level), providing the experimental foundation for a Phase II fabrication and prototype program targeting TRL 6–7.

9. References

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10. Next Steps and Contact

DragonWorx proposes a 60-minute introductory meeting to walk the principal investigator and interested graduate students through the engineering record, discuss which research threads align most naturally with current lab capacity and graduate student research directions, and begin the prior art scoping conversation with the host institution's technology transfer office.

We are genuinely open to a modular engagement — beginning with the one or two threads that represent the strongest natural fit for the partner lab before expanding. The full four-thread program represents the comprehensive picture; the right starting point is wherever the science is most compelling to the lab.

Item	Detail
Company	DragonWorx Biomimetic Technologies
Location	Dallas–Fort Worth metroplex, Texas
Technical contact	getdragons@dragonworx.bio
Website / engineering docs	dragonworx.bio
Platform reference	dragonworx.bio/projects/gripsuit/index.html
Funding status	Seed round in progress — $1.8M target; research collaboration funding contribution structured in parallel
Proposed start	Q4 2026 or subject to partner-lab schedule and graduate student availability
IP negotiation contact	Host institution Office of Research — proposed as joint first meeting

Questions about the engineering record, surface compatibility data, or the broader DragonWorx platform (DragonSuit aerodynamic wingsuit, AquaSuit, JumpSuit) are welcome at any stage. The complete research proposal for the DragonSuit wind tunnel program at UTA is available at dragonworx.bio for reference on the level of engineering documentation DragonWorx prepares for academic partnership conversations.