WEARABLE DUAL-TETHER WEB-SLING SYSTEM

Concept Whitepaper v0.1 - Architecture developed through 8 August 2026

Purpose. Capture the current engineering concept before web-compound and anchor development. This document describes a thin, dual-forearm wearable tether system using distributed pneumatic structures, mechanical load sharing, compact electric drives, redundant braking, and graceful-degradation packaging.

Development boundary: This is an exploratory engineering concept, not certified fall-protection equipment. Any physical prototype should begin as a fixture-mounted/dummy-load system. Human suspension, rappelling, swinging, or building-height testing requires independently engineered and certified life-safety components.

Constraint	Current target
Wearer mass basis	<140 lb (~64 kg)
Primary configuration	Two independent forearm tether modules
Maximum external thickness	<1.5 in / 38.1 mm proud of body
Outer casing	Sacrificial 3D-printed clamshell
Pneumatic concept	Distributed ~2-3 mm microtube fascicles with ambient-air intake
Drive concept	Compact high-RPM BLDC + reduction + capstan
Safety philosophy	Graceful degradation + independent passive structural load path

1. System Vision

The target is a fitted wearable system capable, in principle, of deploying and managing two tether lines from the forearms while keeping the majority of the structural and pneumatic architecture nearly invisible beneath an outer suit.

The design deliberately separates four functions: **tether force transmission**, **shock/load management**, **powered line movement**, and **protective/aesthetic packaging**. No single printed or pneumatic component is intended to be the sole life-safety element.

2. Dual-Forearm / Shoulder Load Architecture

Each forearm is treated as an interface rather than an isolated wrist anchor. Tether forces are routed longitudinally through a rigid or semi-rigid internal forearm spine, past the wrist, toward the elbow and shoulder.

A low-profile pulley/guide network continues over the shoulders and across the upper back. A floating equalizer can mechanically redistribute unequal left/right loading. The geometry is intended to make the shoulder girdle and broad upper-back textile structure participate in the load path while avoiding a conventional bulky climbing-harness appearance.

Important: pulleys redistribute force; they do not erase it. Dynamic catches can create loads many times static body weight. Therefore the load-sharing system must be treated as a force-management layer rather than permission to under-design the primary structure.

3. Anatomical Pneumatic Weave

The suit uses many small pneumatic fibers rather than large cylinders. The current practical target is approximately **2-3 mm outside diameter** tubing, grouped hierarchically like biological muscle: fiber -> fascicle -> muscle group -> regional manifold.

Natural arm and shoulder motion changes the volume of these pneumatic structures. One-way ambient-air intake valves permit fibers to refill as their geometry expands. During rapid compression, restricted exhaust paths resist airflow and produce rate-dependent damping/stiffening.

This differs from a conventional McKibben actuator supplied by a compressed-air tank. Ambient air alone does not provide free positive-pressure actuation; the useful effect comes from **mechanically changing volume, restricting flow, retaining preload, and temporarily compressing captured air**.

4. Baseline Pressure and Free-Air Draw

The intended pneumatic network does not completely empty every cycle. It maintains a modest baseline preload and uses check valves to admit additional ambient air when movement creates additional internal volume.

During a rapid tether load, local tube volumes compress faster than air can redistribute through small restrictions. Local pressure therefore rises temporarily, increasing pneumatic resistance and potentially increasing frictional/jamming effects within the woven bundle. Slow movements allow pressures to equalize and keep the garment compliant.

A master pressure-relief mechanism provides a hard upper bound. Regional relief elements allow localized pressure management without dumping the entire suit.

5. Sacrificial 'Dead Tube' / Pneumatic Fuse Concept

Weaker sacrificial pneumatic elements are interleaved with working fibers. Their intended role is analogous to a fuse: during an abnormal local pressure transient, a deliberately characterized relief membrane/cell vents before neighboring structural pneumatic elements fail.

The garden-hose analogy is useful for understanding restriction: a kink can produce higher pressure upstream while reducing downstream flow, but it cannot create pressure beyond the energy supplied to the system. In the suit, restrictions are therefore used for **pressure zoning, timing, damping, and temporary stiffness**, not free pressure multiplication.

For a wearable system, controlled relief membranes or calibrated valves are preferable to unpredictable tube rupture. A sacrificial event should vent in a known direction and should not create whipping fragments or cascade into adjacent fascicles.

6. Independent Structural Fiber Network

A separate non-pneumatic textile/fiber network remains underneath or alongside the pneumatic weave. Its purpose is simple: loss of pneumatic pressure must produce a degraded suit, not loss of attachment.

Candidate structural classes for later evaluation include UHMWPE, aramid, and other high-specific-strength fibers. Final material selection depends on bend fatigue, abrasion, knot/termination efficiency, heat, creep, and dynamic-load testing.

7. Forearm Drive Cartridge Mk.1

The current cartridge envelope is approximately **280-320 mm long x 65-80 mm wide x <=38 mm maximum external height**, conforming partially around the forearm rather than forming a rectangular box.

The conceptual mechanical sequence is: **motor -> reduction -> clutch -> traction capstan -> mechanical brake -> line guide -> deployment section**. A separate low-load storage reel stores tether length; the traction capstan carries the significant line force.

Separating traction from storage prevents changing storage-spool diameter from strongly changing line speed and reduces the structural demands on the storage reel.

8. Motor / Reduction Concept

A representative compact motor class is a ~30 mm diameter high-speed brushless DC motor. Commercial examples in this envelope can operate well above 10,000 RPM; the design study considered approximately **10,000-16,000 RPM** before reduction.

Reduction converts high motor speed into usable capstan torque. A conceptual range around **25:1-50:1** remains under study and will ultimately be selected from tether diameter, desired line speed, available motor torque, thermal limits, and brake requirements.

The current design preference is two distributed drives rather than one large central motor. This preserves bilateral control and packaging symmetry, although the final system must remain safe under single-side failure.

9. Braking and Fail-Safe Behavior

The motor controller is not considered the sole brake. The conceptual stack is: regenerative/electronic braking for normal control, a normally-engaged mechanical friction brake for power-loss safety, and a passive anti-free-spool mechanism as an additional layer.

A power failure should move the system toward a mechanically arrested state rather than uncontrolled payout. Release and emergency-disconnect behavior must be designed separately so a jam does not trap the wearer.

10. Shell and Mechanical Containment

The outer 3D-printed shell is sacrificial: it provides shape, abrasion protection, aerodynamic smoothing, component access, and aesthetics. It is not the primary tether anchor.

Inside it is a tougher containment layer around gears, capstans, cables, and pinch points. The actual tether force transfers into a dedicated structural spine/rail and then into the distributed textile load path.

Design objective: an outer-shell fracture should be cosmetically dramatic but mechanically boring. Moving parts remain contained and the primary structural system remains intact.

11. Energy Reality

The pneumatic weave can absorb, redistribute, and temporarily store mechanical energy, but it cannot create the sustained energy required for repeated powered ascent. Powered vertical movement therefore still requires an energy source.

The present architecture uses distributed electrical storage driving BLDC motors, with pneumatic structures handling compliance and load management. Future energy-recovery work could investigate regenerative descent and elastic/pneumatic buffering, but those should be treated as efficiency improvements rather than primary energy sources.

12. Major Open Problem: Web / Tether / Anchor

The web compound and deployment/attachment design remain intentionally unresolved. This subsystem determines tether diameter, storage volume, capstan geometry, braking loads, useful range, and the feasibility of any real-world anchoring method.

Any eventual building-use anchor must be demonstrably structural. A visually successful attachment that cannot be verified to carry dynamic human loads is not an anchor.

13. Failure Philosophy

The system is being designed around **graceful degradation**: outer shell failure, loss of one pneumatic zone, loss of electronics, or loss of active damping should each leave progressively less capability rather than immediately causing catastrophic loss of the primary load path.

Critical failure modes to test include puncture, tube/manifold rupture, pressure-regulator failure, stuck valve, jammed capstan, brake failure, motor/controller loss, one-line loading, structural-spine damage, pulley seizure, tether abrasion, and asymmetric shock loading.

14. Prototype and Validation Ladder

Development should proceed from non-wearable tests upward: pneumatic-fascicle coupons; manifold/relief tests; structural forearm-spine pulls; capstan/brake fixture testing; complete cartridge dummy loads; instrumented asymmetric two-line tests; and only after independent engineering review, low-energy wearable evaluations.

Building-height suspension or swinging is outside the Mk.1 validation scope. Dynamic human-load equipment should use independently rated/certified life-safety components and professional structural anchoring.

15. Current Architecture Snapshot

Outer suit - aesthetic/abrasion layer.
Sacrificial printed shell - protects cartridge.
Inner containment cage - isolates moving mechanisms.
Structural spine - transfers tether force past the wrist.
2-3 mm pneumatic fibers - distributed damping/stiffening.
Sacrificial relief cells - localized pneumatic fuses.
Shoulder/back equalizer - passive bilateral load redistribution.
Independent structural textile - survival load path.
High-RPM BLDC + reduction - powered tether management.
Traction capstan + separate storage reel - compact line handling.
Normally-engaged brake - power-loss arrest.
Ambient check valves + pressure relief - tankless pneumatic breathing architecture.

16. Immediate Next Engineering Work

With the system architecture now defined, the next design pass should concentrate on: (1) web/tether material and diameter; (2) attachment/anchor concept; (3) capstan geometry; (4) exact motor/gearbox operating point; (5) brake sizing; (6) pneumatic fascicle weave patterns; and (7) a benchtop pressure/load test article.

Those selections will convert the current concept from architectural dimensions into CAD dimensions and measurable performance targets.

Engineering Note

This whitepaper intentionally records the concept before material optimization. Numerical values are preliminary design targets, not certified ratings. No component should be assumed suitable for supporting a person until its complete assembly, terminations, redundancy, dynamic response, and failure modes have been independently validated.