

Omnidirectional compliant hinge: a caterpillar-inspired joint for multi-axis motion

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Abstract

Kinetic systems enable environmental adaptability in buildings, but rigid-body joints introduce friction and wear that limit long-term reliability. Compliant mechanisms, which achieve motion through elastic deformation, eliminate these failure modes, but existing systems remain largely constrained to uniaxial articulation. This research presents an omnidirectional compliant hinge that achieves multi-axial bending with a pneumatically actuated membrane-tensegrity system, developed through biomimetic abstraction of the tobacco hornworm (*Manduca sexta*). The hornworm's motion arises from three functional principles: a segmented integument for flexibility, a hydrostatic skeleton for structural rigidity, and longitudinal musculature for curvature control, each of which finds a direct analogue in the proposed system. Additively manufactured rigid struts bonded onto a pre-tensioned elastic textile form a membrane-tensegrity shell replicating the integument's graded stiffness behavior, while McKibben pneumatic muscles, arranged longitudinally within the shell, jointly abstract both the hydrostatic and muscular functions: differential pressurization produces directed bending, while simultaneous inflation stabilizes configured states without locking mechanisms. Experimental evaluation confirmed 345° of omnidirectional angular coverage and tilt angles exceeding 60°, achieved within a lightweight, friction-free, mechanically monolithic assembly. This work presents an architectural-scale demonstrator of omnidirectional compliant articulation, with potential applications in kinetic façades and dual-axis solar tracking.

Keywords: compliant mechanisms, membrane-tensegrity, adaptive envelopes, kinetic architecture, bio-inspired design, pneumatic actuation, McKibben muscles, omnidirectional bending, additive manufacturing, multi-axis motion

1. Introduction

Kinetic building envelopes have emerged as a compelling design strategy for achieving environmental responsiveness, solar control, and spatial adaptability. Systems such as the Al-Bahar Towers (Arup, 2012), the One Ocean Pavilion (SOMA, 2012) and the FlectoLine facade (ITKE/ITFT, 2024) demonstrate the potential of articulated envelopes to modulate thermal gain and ventilation. As climate targets raise performance demands, such systems increasingly call for precise multi-axis orientation, particularly for solar tracking, where angular precision directly determines photovoltaic output.

The predominant technical approach to kinetic articulation relies on discrete rigid-body mechanisms, such as hinges and ball joints, which introduce friction, backlash and mechanical fatigue under cyclic loading. The Institut du Monde Arabe's adaptive facade (Jean Nouvel, 1987), became largely non-functional within six years of operation due to the compounded maintenance demands of its 240 motorized apertures [1]. More broadly, empirical assessments of kinetic facade systems identify

mechanical complexity as a primary barrier to long-term operational reliability [2]. These limitations are inherent to rigid-body kinematics, which require relative motion between discrete components, resulting in wear over time.

Compliant mechanisms, which achieve motion through the elastic deformation of continuous material, offer a more resilient alternative. By eliminating discrete components, they inherently remove friction and backlash, failure modes characteristic of conventional joints. In architectural applications, this strategy has been productively explored through glass-fiber-reinforced polymer (GFRP), as in the Flectofin shading system [3] and FlectoLine facade [4], as well as through hygromorphic actuation, as in the Solar Gate project [5]. These systems achieve lightweight, maintenance-free actuation with high cyclic durability. However, a systematic limitation persists: current architectural compliant mechanisms are largely constrained to uniaxial or planar bending, arising from anisotropic material layups or fold geometries. This restricts their applicability in scenarios requiring multi-axial spatial reorientation, precisely the condition demanded by dual-axis solar tracking or spatially graded adaptive envelopes. The closest analogues in engineering, continuum robotic manipulators and tensegrity-based soft robots, demonstrate that omnidirectional compliant articulation is physically achievable [6][7], yet these systems have not been translated into architectural-scale mechanisms.

This research addresses that gap by asking: can soft-body biological principles enable compliant omnidirectional articulation at architectural scale? To answer this, we draw on the biomechanics of the tobacco hornworm (*Manduca sexta*), a soft-bodied insect larva capable of smooth, continuous bending in any spatial direction without rigid skeletal elements. Its motion arises from the coordinated interaction of a segmented integument, hydrostatic stiffness, and longitudinally arranged musculature. Through a biomimetic abstraction process, these principles were translated into an architectural-scale demonstrator: a cylindrical membrane-tensegrity shell formed by additively manufactured rigid ribs bonded onto a pre-tensioned elastic textile, actuated by four longitudinally arranged McKibben pneumatic muscles. The textile establishes a global tension field mirroring the caterpillar cuticle, while the ribs act locally in compression, replicating segmental stiffness modulation. Differential muscle pressurization produces omnidirectional bending without mechanical hinges, while simultaneous pressurization of all muscles increases geometric stiffness and stabilizing configured positions. Experimental evaluation confirms omnidirectional articulation under external load, achieved within a lightweight, friction-free, and mechanically monolithic assembly.

2. Methods

2.1. Biological abstraction

Omnidirectional compliant bending is widespread in biological systems, enabling organisms to navigate complex environments without rigid joints. From a broader survey of ten species, including insects, soft-bodied invertebrates, and plants, four biological role models were selected for further investigation: the giant ichneumon wasp (*Megarhyssa macrurus*), the Japanese rhinoceros beetle (*Allomyrina dichotoma*), the compost worm (*Dendrobaena veneta*), and the tobacco hornworm (*Manduca sexta*). Because the tobacco hornworm's mechanism does not require a rigid substrate [10], a deformable scaffold [11], or fluid pressurization [12], *Manduca sexta* was identified as the strongest candidate for a kinetic facade application. Its bending behavior emerges from three key features: a compliant integument for large deformation, hydrostatic rigidity for load resistance, and longitudinal musculature for active control (see Figure 1).

2.1.1. Segmented integument

Manduca sexta's segmented integument balances global flexibility with local stiffness. The cuticle operates as a fibre-reinforced composite, with chitin nanofibrils embedded in a cuticular protein matrix

providing structural integrity [13], while regionally varying protein ratios and hydration levels tune local elasticity [14]. Together with internal pressure, the integument's graded stiffness allows the hornworm to precisely modulate its flexibility and rigidity in response to varied positions and load cases [10].

2.1.2. Hydrostatic skeleton

Manduca sexta relies on a hydrostatic skeleton to provide rigidity and structural reinforcement to its otherwise soft body. Its internal cavity, or hemocoel, is filled with hemolymph, an incompressible fluid that functions as a load-bearing medium. Contraction of the surrounding body-wall muscles increases internal hydrostatic pressure, enabling the caterpillar to maintain posture, transmit forces, and support bending deformations under external loading. Unlike annelids, this pressure is not used for locomotion, which is instead achieved through curvature changes generated by lengthwise muscles [10].

2.1.3. Longitudinal musculature

Manduca sexta's predominantly longitudinal muscles locally shorten the body to produce bending, whereas oblique muscles enable torsion. Each muscle is controlled by only one or two neurons, relying instead on the dynamic properties of the “super-contracting” muscles themselves, which generate 60% of peak force between 65% and 160% of optimal length [16], to process environmental information. This system of embodied computation demonstrates potential for regulated bending with low control complexity [15].

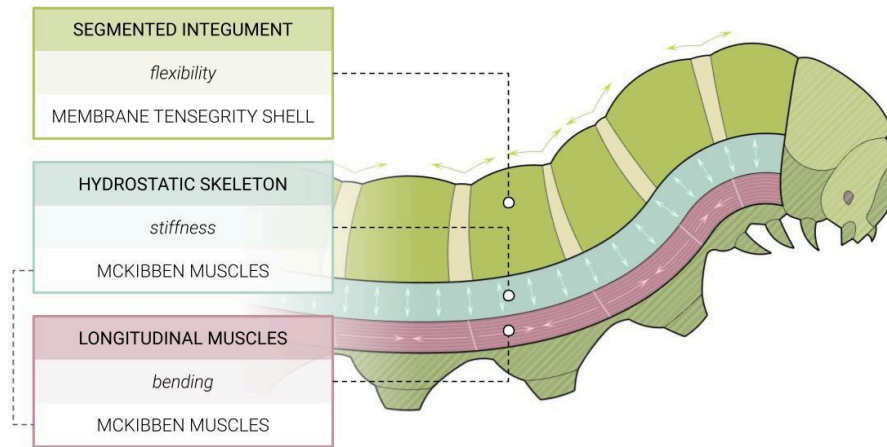


Figure 1: Biological abstraction of *Manduca sexta*'s segmented integument, hydrostatic skeleton, and longitudinal musculature.

2.2. Technical implementation

The biological abstraction identified three functional principles governing *Manduca sexta*'s omnidirectional bending: a compliant, stiffness-graded integument; a hydrostatic skeleton providing load-bearing rigidity; and longitudinally arranged musculature enabling active curvature control. These principles were translated into two integrated technical subsystems: a membrane-tensegrity shell replicating the integument's graded compliance, and four McKibben pneumatic muscles jointly abstracting both the hydrostatic stiffening mechanism and the longitudinal musculature. Together, these subsystems form a mechanically monolithic actuator capable of omnidirectional bending without discrete joints.

2.2.1. Membrane-tensegrity shell

A membrane-tensegrity approach was adopted to replicate the integument's functional logic, a compliant membrane stabilized by discrete stiff inclusions, which enables large global curvatures without local buckling. Discontinuous rigid elements were additively manufactured in PETG directly onto a biaxially stretched elastic jersey textile. Upon release from the build plate, the contracting textile induces a continuous pretension field between the rigid elements, in which the textile acts globally in tension and the elements act locally in compression. The geometry of the rigid elements critically determines the shell's bending behavior. Four element geometries — lines, crosses, V's, and Y's — were evaluated based on the minimum radius of curvature achieved before buckling (Figure 2). Alternating V's produced the smallest radius, followed closely by alternating Y's, while lines and crosses buckled at significantly larger radii. The asymmetric V and Y forms generate greater circumferential than longitudinal stiffness, resisting lateral buckling as curvature increases, while their ability to nest under contraction provides progressive geometric stability at high bending angles. This inverts the optimization target of Tracy et al. [17], whose worst-performing patterns for rigid shell applications proved most effective here because circumferential compliance resistance, rather than global isotropy, is the governing criterion. Alternating V's were selected for the final prototype on the basis of bending performance.

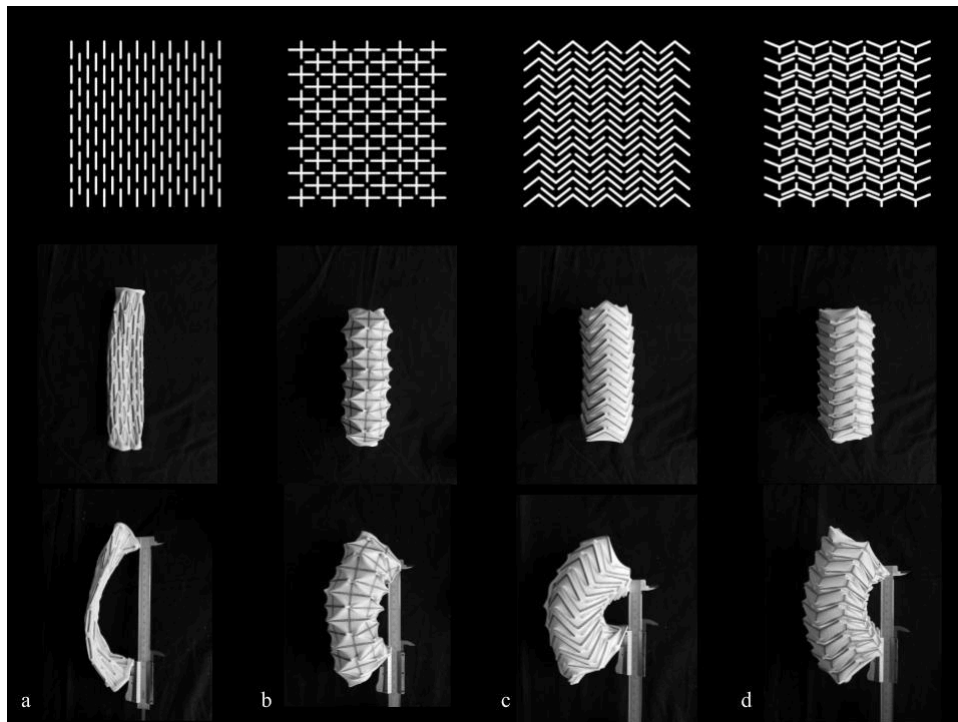


Figure 2: Tests of rigid element shapes: lines (a), crosses (b), V's (c), and Y's (d), as a pattern (top row), as a tube (middle row), and during bending (bottom row).

2.2.2. McKibben air muscles

Hydrostatic stiffness and longitudinal musculature in *Manduca sexta* were jointly abstracted using McKibben air muscles, which combine load-bearing capability with active contraction. These actuators consist of an elastomeric tube enclosed within a braided mesh sleeve. Upon inflation, radial expansion of the tube is constrained by the braid geometry, converting internal pressure into axial contraction. This results in a muscle-like behavior in which increasing internal pressure simultaneously generates tensile force, shortens the actuator, and increases its effective stiffness.

To replicate the dominant longitudinal muscle arrangement of the caterpillar, four McKibben muscles were positioned symmetrically on the interior of the membrane-tensegrity shell. Directional control is achieved through differential activation: a single contracting muscle induces bending toward that side; coordinated activation of multiple muscles allows for smooth omnidirectional curvature and more complex spatial movements. Control of the system is achieved through a four-way valve, allowing each actuator to be pressurized independently or in combination. The system can be operated using either a hand-powered pump or a small compressor.

2.2.3. Integrated system

The two subsystems interact to produce the complete bending behavior. The membrane-tensegrity shell provides the global compliance and buckling resistance within which the muscles operate; the muscles supply both the active curvature and the geometric stiffening that stabilizes each configuration. To assemble the system, the McKibben muscles were first sewn to the interior of the flat textile composite at the top and bottom V-elements, positioning each actuator longitudinally along the future shell's inner surface. The textile composite was then formed into a cylinder by joining the overlapping edge columns, enclosing the muscles within the shell. A rigid connector plate was attached to the uppermost V-elements, providing a fixed mounting point for vertical installation and load application. The four muscles were connected to the four-channel valve via individual supply lines, completing the pneumatic circuit. The resulting assembly is mechanically monolithic: all motion arises from elastic deformation of the textile and contraction of the muscles, producing a friction-free, low-maintenance kinetic system.

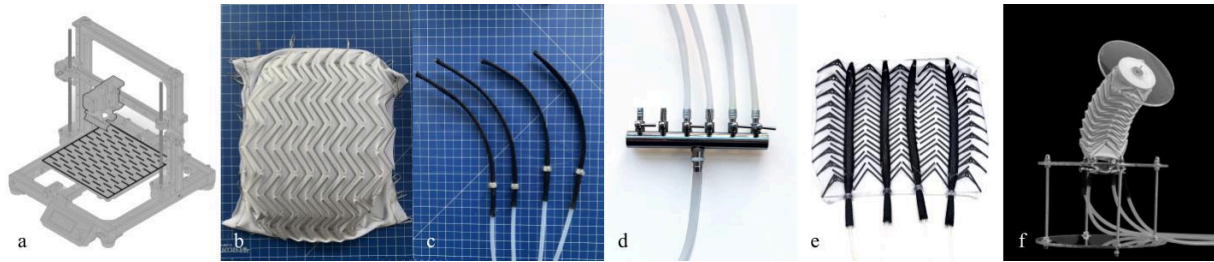


Figure 3: Fabrication process: (a) 3D-printing on stretched textile, (b) released membrane-tensegrity shell, (c) assembled McKibben muscles, (d) four-way valve, (e) McKibben muscles sewn onto shell, (f) shell riveted into a tube, capped with a connector plate and panel load, and mounted on a stand.

2.3. Experimental Evaluation

To assess the demonstrator's omnidirectional bending capability and load-bearing performance, a 70g circular Plexiglass panel was attached to the upper connector plate, simulating the mass and geometry of a solar panel mounted on the actuator tip. To establish a consistent spatial reference for correlating muscle position with bending direction, the four muscles were assigned cardinal labels (North, East, South, and West) corresponding to their circumferential positions within the actuator. These labels are used throughout the following test descriptions and results.

2.3.1. Omnidirectionality

To determine angular coverage, the demonstrator was photographed from above for each muscle and intercardinal pair at a range of pressures up to 1.25 bar. From each overhead photograph, a line was drawn from the centroid of the actuator base through the displaced tip and its bearing was measured relative to a fixed horizontal reference, with 0° corresponding to East, 90° to North, 180° to West, and 270° to South. This allowed the directional distribution of bending across muscle configurations and

pressure levels to be mapped across the full 360° range. This test established whether the system could achieve full omnidirectional articulation or was constrained to discrete bending directions.

2.3.2. Bending

To characterize bending performance under self-weight and panel load, the demonstrator was mounted vertically and photographed from the side for single muscles, intercardinal pairs, and all muscles at a range of pressures up to 1.25 bar. All photos were taken in a single session with a leveled camera to ensure angular measurements were taken from a consistent reference plane. Two angles were extracted from each image by overlaying reference lines: inclination angle, defined as the deviation of the actuator tip from vertical, and tilt angle, defined as the deviation of the attached panel from horizontal. These metrics were recorded across pressure levels and muscle configurations to characterize the relationship between actuation input and bending output.

2.3.2. Load capacity

To evaluate stiffness and curvature control under gravitational loading in a facade-mounted configuration, the demonstrator was repositioned horizontally, replicating a condition in which the actuator projects outward from a building facade with gravity acting transversely. Images were taken from the side under each muscle configuration at a range of pressures, again with the camera leveled. The inclination angle was redefined as the deviation of the actuator tip from horizontal, and tilt angle as the deviation of the panel from vertical. In this configuration, gravity causes passive downward droop; the goal of actuation was therefore to minimize both angles, demonstrating the system's capacity to counteract external loads through internal pressurization.

4. Results

4.1. Omnidirectionality

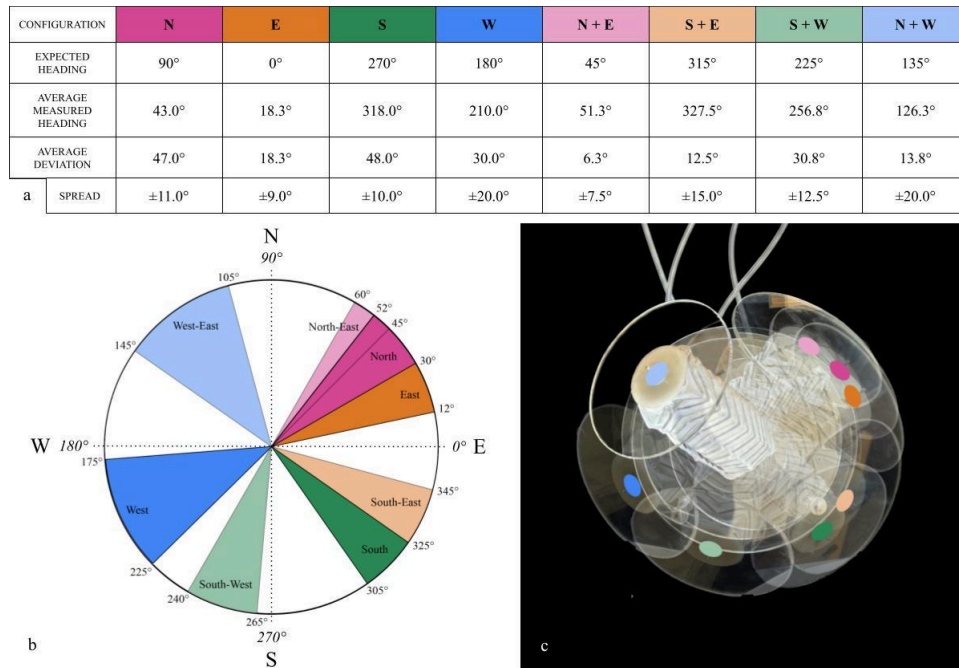


Figure 4: Omnidirectional bending under single- and double-muscle actuation. The table (a) and polar diagram (b) show angular displacements; the composite image (c) an instance of each configuration, covering 345°.

The omnidirectionality test revealed a broad angular coverage of 345° , albeit with significant deviations between predicted and actual headings. Bending towards cardinal directions was achieved by actuating one muscle at a time and intercardinal directions by actuating adjacent pairs. Figure 4 shows the angular displacements induced by each muscle configuration, which on average deviated by 25.8° from the predicted heading with a spread of 26.3° . Paired configurations yielded 20.0° less angular deviation on average than single-muscle configurations, suggesting that co-contraction partially compensates for individual muscle inconsistencies. Activation of all four muscles simultaneously returned the panel to a near-vertical orientation.

4.2. Bending

The bending test revealed distinct deformation behaviors depending on muscle configuration and applied air pressure. Single-muscle activation produced the largest directional bending, with inclination angles reaching approximately 41° and tilt values exceeding 60° at air pressures between 1.0 and 1.3 bar. Compared to single-muscle activation, paired muscles generated more stable deformation and reduced maximum angular displacement, with inclination angles ranging from 13° to 36° and tilt values reaching 56° . In contrast, simultaneous activation of all four muscles minimized bending and tilt, with values remaining below $10\text{--}15^\circ$ even at higher pressure levels. The plotted results show a positive correlation between air pressure and both inclination and tilt angles, as well as distinct clustering between single-, paired-, and four-muscle configurations, although some variability in actuator response was observed within each group.

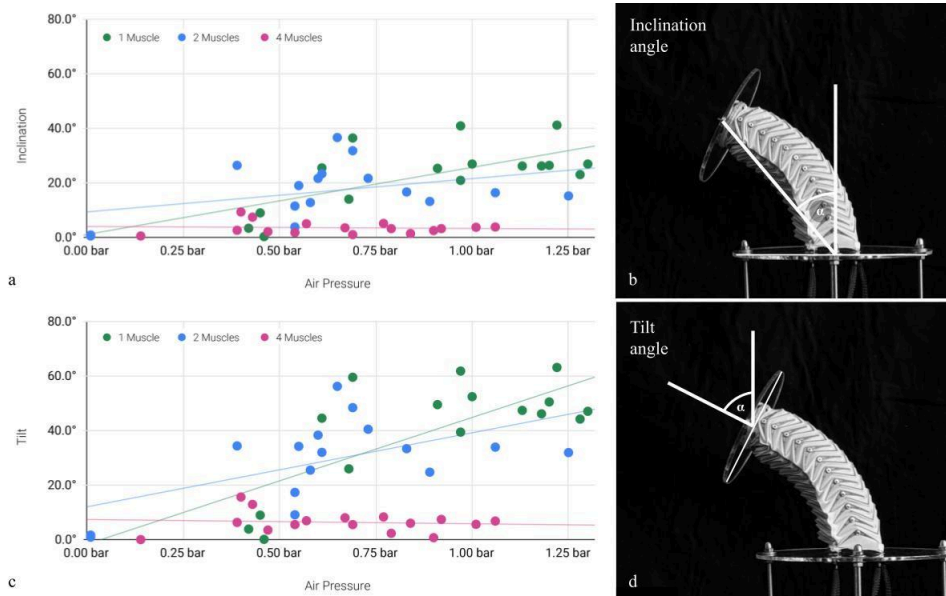


Figure 5: Inclination (a) and tilt (c) angle variation during bending tests under pneumatic actuation across different muscle configurations. Reference images (b, d) illustrate the measurement method.

4.3. Load capacity

The load-bearing test examined the ability of different muscle configurations to resist gravity load at varying air pressures. All configurations exhibited a negative correlation between air pressure and both inclination and tilt angles. Single-muscle activation showed the steepest reduction in tilt relative to inclination, with tilt values decreasing from $49\text{--}54^\circ$ at low pressure to below 9° above 1.0 bar, while inclination decreased from $38\text{--}41^\circ$ to $19\text{--}28^\circ$. Four-muscle activation produced the most uniform reduction in both angles, with inclination decreasing to $14\text{--}22^\circ$ and tilt dropping below 30° above 1.0

bar. Three-muscle configurations occupied an intermediate regime, exhibiting greater passive stiffness and reduced actuation efficiency per unit pressure.

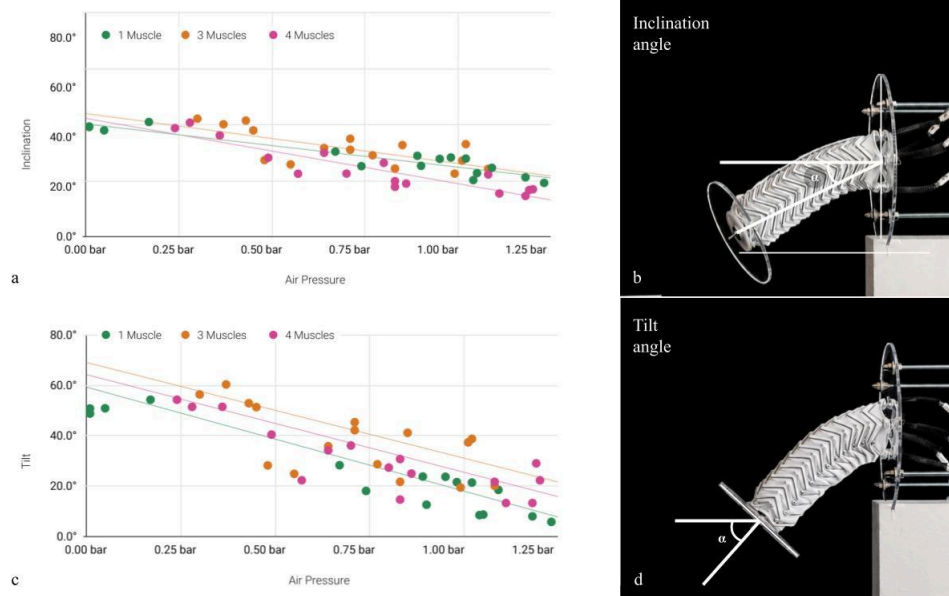


Figure 6: Inclination (a) and tilt (c) angle variation during load testing under imposed horizontal deflection across different muscle configurations. Reference images (b, d) illustrate the measurement method.

5. Discussion

The experimental results confirm that the proposed actuator achieves near-full omnidirectional articulation and active bending under pneumatic control without discrete mechanical joints. Single-muscle activation produced inclination angles of up to 41° and tilt values exceeding 60° at pressures between 1.0 and 1.3 bar, while the full actuation envelope spanned 345° of angular coverage. These results validate the core hypothesis that soft-body biological principles can be translated into a compliant, hinge-free mechanism capable of multi-axial articulation at architectural scale.

Several limitations of the current prototype should be acknowledged. The most apparent is the asymmetrical bending behavior observed across muscle configurations, primarily attributable to the riveted seam used to close the membrane-tensegrity tube, which locally increased stiffness on one side of the shell. This is likely responsible for the 25.8° average angular deviation from expected and remaining 20° gap in directional coverage. A less obtrusive joining method, such as curved-needle sewing through the rigid elements, could address this in future iterations. The attachment of the McKibben muscles introduced additional asymmetry: muscles cut to match the tube length in their relaxed state restricted bending on the opposite side, while cutting them slightly longer introduced slack that occasionally caused entanglement within the tube. A slightly elastic braided sleeving for each muscle would constrain their position while permitting elongation beyond the relaxed state, more closely replicating the behavior of *Manduca sexta*'s musculature and eliminating both failure modes simultaneously. The elastomeric tubes used for the McKibben muscles ruptured at approximately 1.5 bar, limiting contraction force and geometric stiffness and restricting load-bearing tests to a 70g Plexiglass panel. Thicker elastomeric tubing capable of sustaining higher pressures, combined with increased textile pre-stress applied during additive manufacturing, would improve load capacity in subsequent prototypes.

6. Conclusion

This work presents an omnidirectional compliant hinge developed through biomimetic abstraction of the tobacco hornworm (*Manduca sexta*), demonstrating that soft-body biological principles can be translated into a hinge-free, pneumatically actuated mechanism capable of multi-axial articulation at architectural scale. The proposed system extends the trajectory established by architectural compliant mechanisms such as the FlectoLine facade module, which achieved a robust photovoltaic-integrated panel with a bending range of $\pm 80^\circ$ along a single axis. The present demonstrator achieves a comparable bending amplitude of approximately $\pm 60^\circ$ while distributing that motion across 345° of rotation. Relative to soft robotic continuum manipulators, which have demonstrated omnidirectional compliant articulation in laboratory settings, this work represents one of the first translations of that capability into an architectural-scale mechanism designed for facade integration.

As a prototype developed within the scope of an Architectural Biomimetics seminar, this work remains in its early stages. Proving viability as a facade component will require cyclic load testing to characterize fatigue strength and scalability studies to assess its potential for architectural applications. The robustness of the system under loads encountered in outdoor deployment (especially wind, but also snow and thermal cycling) has yet to be analyzed. A field-deployed system would require an automated control architecture to replace the manually operated valve used in testing. While synchronously actuating multi-module arrays could remain simple, differentiated actuation would be a significant engineering undertaking. Machine learning approaches might further optimize actuation sequences for energy-efficient tracking while respecting structural load limits. Addressing these challenges would represent meaningful steps toward evaluating the omnidirectional compliant hinge as a viable architectural system beyond the demonstrator scale.

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