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Architecture and Soft Kinetics: Scale and Performance

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DIGITAL TECHNOLOGY

ABSTRACT - *Traditionally buildings are not designed to adapt to the dynamics of fluctuating environmental conditions or changing user needs. Even though today's technical capabilities for kinetics have advanced significantly, the integration of stable and kinetic elements still presents challenges. The project described in this article integrates "soft" and "hard" elements to produce a dynamic material system that is self-supporting, pliable, and kinetic. It explores a kinetic and formal potential of integrating custom-made soft robotic muscles into a component-based surface. The developed prototype is a light modular construct, with components and patterns of aggregation that work in unison with the silicone muscles to produce a dynamic structure. The proposed material system can be used to construct a kinetic and "programmable" architectural skin that can be integrated with existing or new façade systems. The project is informed by a history of pneumatic structures, the technology of soft robotics, and a kit-of-parts design strategy.*

Keywords: inflatable actuators, kinetic architecture, modular structure, pneumatic structures

Climate action is an ethical imperative for today's society. As is widely reported, the building industry contributes forty percent of CO_2 emissions globally through the production of building materials, construction, building operations, handling of waste, or encroachment on the land that otherwise acts as a carbon sink. The architectural profession, implicated in its position as part of the building industry, faces the need to address the ever-increasing challenges of climate change. Architectural adaptation, the built environment's capacity to respond dynamically to changes in the internal or external environment, has been one successful way to offset the industry's energy consumption. A new frontier in material research and technology, transferred from adjacent disciplines like robotics, embedded electronics, and bioengineering, has enabled architects to explore new ways that buildings can interface with their environment. While architecture is increasingly employing kinetic solutions that make a building envelope more adaptable, the question is still "how" adaptive systems, and more precisely kinetics, can be incorporated into building elements, surfaces, or structures. Some of the challenges in working toward a more seamless integration of kinetics with otherwise static building elements lie in the connection between static and kinetic components, and the mechanics necessary to facilitate their movement.

Contemporary adaptive building skins can actively respond to changes in sun exposure, as seen in projects such as the: Q1 Headquarters building for ThyssenKrupp in Essen, Germany, designed by Chaix & Morel (Paris) and JSWD Architekten (Cologne); Al-Bahr Towers, in Abu Dhabi, UAE, designed by AHR; One Ocean pavilion for Expo 2012 in Yeosu, South Korea, designed by SOMA from Vienna, Austria; or Council House 2 (CH2) building in Melbourne, Australia, designed by Mick Pearce. But what is typical in these (and other) buildings with adaptive skins is their reliance on mechanical or hydraulic systems of actuation.[1] While these are certainly effective and proven ways of producing kinetic transformation, they are also complex, costly, noisy, and produce vibration. Their large-scale motors and other mechanical parts are high in maintenance requirements and electricity consumption. Meanwhile, methods based on non-mechanical actuation or intrinsic material system behaviors, would require less energy-intensive solutions and less components for connections.

Material-based actuation could be a viable way to make adaptive building components lighter, more flexible, and compact because, among other things, the material itself can actuate and sense surrounding conditions, reducing the need for additional elements. Examples that demonstrate the performative aspects of active material systems include: Bloom canopy by Doris Sung, installed in the courtyard of M&A Gallery in Silver Lake, Los Angeles; HygroScope by Achim Menges and his Institute for Computational Design and Construction (ICD) research group at the University of Stuttgart, Germany; or the experimental Homeostatic Façade System by Decker Yeadon LLC. This work suggests a different kind of material and structural economy that takes into account dynamics and responsiveness as criteria for performance. The "Soft Kinetics" project presented here explores material integration between kinetics and stasis by incorporating the material behaviors of inflatable components with a component-based system to produce an adaptive and dynamic material system. The main contribution of this project is a new model of lightweight envelope system made of self-similar modular components and capable of dynamic adjustment. The project attempts to address two challenges in designing dynamic and adaptive surfaces (a low energy, non-mechanical actuation system, and the articulation of corresponding surface tectonics that facilitate the smooth integration of kinetic elements) and in doing so, introduces the innovative employment of “pneu” structures.

SCALE OF SOFT KINETICS: FROM INFLATABLE STRUCTURES TO INFLATABLE COMPONENTS

The Soft Kinetics project is in part informed by a history of pneumatic structures and the technology of soft robotics. It brings together properties of flexing spatial enclosures suggested by experimental pneumatic structures of the past, and the performative kinetic facility of soft inflatable components used in soft robotics, to instigate movement (Fig. 1). Pneumatic structures brought to architecture a new kind of formal language that not only changed the aesthetic expression but also began to question the permanence and rigidity of architectural enclosures. These structures hinted at a new relationship between the human body and space, and promoted the use of inexpensive, easily available, and lightweight plastic material. They brought to architecture a sense of non-rigid materiality. The elastic inflatable form of soft robotic actuators speaks to this compliant materiality, and it is the actuators’ capacity to produce motion that is particularly important for the development of the Soft Kinetics project.

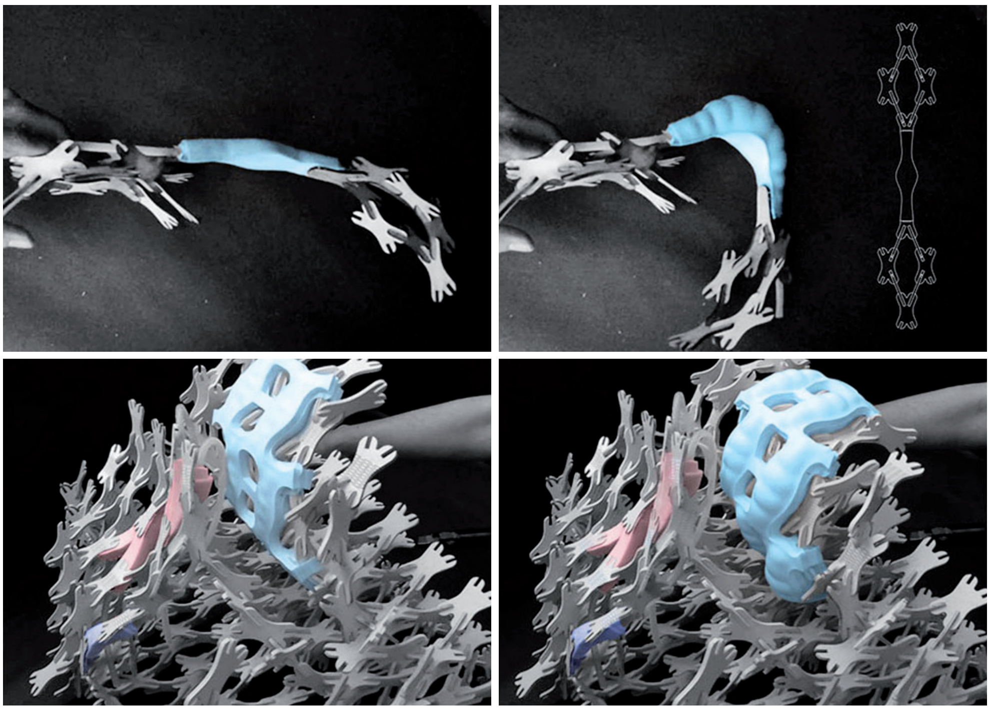

Figure 1. When activated, pneumatic muscles make parts of the structure kinetic enabling opening, closing, or shifting of the structure’s regions.

Early inflatable or pneumatic structures were used primarily for their lightness in relation to their structural span. Developed by the U.S. military through the research of Cornell Aeronautical Lab engineer Walter Bird, they deployed radio antennae in 1948 and had a strictly utilitarian role. Bird's radome, built in the late 1940s, was one of the first fully inflatable structures. Between the 1940s and 70s, the exploration of these kinds of structures grew beyond their intended use. The simple, rudimentary form of inflatable architecture gave rise to several other examples that followed the original utilitarian trajectory, but also paved the way for these structures to enter the broader public sphere.

In the late 1950s, Bird collaborated with Paul Weidlinger on an inflatable roof for the Boston Arts Center Theater. This collaboration popularized the use of inflatable technology.[2] In the 1960s, the US Atomic Energy Commission's mobile pneumatic theater was designed by Victor Landy and Walter Bird. The theater traveled for a decade to different parts of the world as part of the U.S. Atoms for Peace program. During that time, it not only established peacetime possibilities for atomic energy, but it also exposed the deployable potential of pneumatic structures.[3] This potential was fully expressed at the end of the decade at the Osaka World's Fair, Expo '70, in what seemed at the time to be the culmination of pneumatic architecture invention: [4] The Fuji Group Pavilion designed by Yutaka Murata was built from a series of air-inflated vinyl tubes bound together to form a larger structure. The shift from a single inflated volume (radome) to the aggregation of inflated tubes presented an innovative moment in building large-span pressurized structures.

In the 1960s and 1970s, air-supported structures were used in many speculative and experimental works of architecture. Besides their self-supporting structural capacity, inflatable structures offered a new prospect for designing soft and transformable spaces with new formal and dynamic qualities. Their scale also changed: Experimental proposals by Coop Himmelb(l)au, Haus-Rucker-Co, Ant Farm, and Archigram created structures at the scale of the human body. A new kind of architectural space emerged that operated as an extension of the immediate body space, utilizing the soft and temporal qualities of inflatables. Coop Himmelb(l)au's Villa Rosa, for example, even allowed for a change of volume by inflation. These inflatable, mobile, and temporary structures were acknowledging the transformational potential of the inflatable form, and spatial boundaries were no longer defined by rigid material enclosures. The proliferation of these structures was also a reflection of the cultural and political moment of the late 1960s, and an extension of the critique of architecture, urbanism, and everyday life started by Situationists in the late 1950s and continued by Archigram in the early 1960s. Ephemerality and mobility afforded by pneumatic structures reflected a new cultural imagination that stood in opposition to the inertness and repressive qualities of postwar architecture and urbanism.[5]

Even though pneumatic architecture did not really provide an alternative to architectural permanence, it emphasized the performative aspects of architecture, or what Reyner Banham, the late British architectural critic and historian, referred to as “shelter performance.” [6] His fascination with the behavior of pneumatic enclosures as one enters and exits is described in his 1968 essay “Monumental Wind-bags”: Banham likens this soft and responsive structure to a living organism and laments upon conventional architecture’s rigidity and general lack of responsiveness to the dynamics of the environment or use. The theme is also present in his essay “A Home Is Not a House,” where he proposes a pneumatic environment equipped with the latest environmental and entertainment systems, wrapped in a transparent and deployable enclosure, alluding to technology’s capacity to deliver a radically different way of living. The scale of “shelter performance” was pushed to the extreme by radical proposals like Buckminster Fuller’s massive dome over Manhattan, and Frei Otto’s vision to shelter 40,000 people in the Arctic Circle; though often dismissed as purely speculative, these projects are grounded in an understanding of the performative capacity of spherical form to reduce energy use. Fuller calculated the sum of all exterior building surfaces that would be covered by his dome and found it to be eight times greater than the surface of the dome itself, concluding that, in terms of surface exposure, the dome would significantly reduce energy input necessary to temper the enclosed environment.[7]

Current research experiments in pneumatic form are fueled by the performative aspect of elastic pneumatics brought down to smaller scale inflatables. The change in scale allows their integration into architectural assemblies. These experiments, influenced by soft robotics, suggest a new trajectory in the exploration of dynamic spatial boundaries where actuation is integral to their tectonics. In soft robotics, actuators are made from “soft” materials: materials such as shape memory alloy, electroactive polymers, or silicone elastomers are used for these purposes. From the design point of view, soft actuators produce soft deformations and lifelike movements, offering a large degree of freedom when conceptualizing adaptive building systems.[8] Powered by these subtle movements, building skins could act as interactive layers, adjusting, for example, in real time to the sun’s movement pattern. If equipped with a power-generating source such as photovoltaics, these building skins, as low energy consumers themselves, could further reduce energy consumption by acting as shading devices.

Several experimental research projects point to a new potential for pneumatic structures. The “PneumaKnit” by Sean Ahlquist, Wes McGee, and Shahida Sharmin (2017) [9] explores motion and the geometric articulation of inflatable components using knitted constraints. Instead of relying on the shape of the actuator to produce a specific motion, knitted constraints regulate its expansion. The emphasis is on the material structure of the knitted constraint which, through a density of its weaves, produces the particular actuator transformation. This project is concerned not only with the actuator itself but also with the integration of an actuator with its constricting surface, a partnership that works in unison to produce the desired effect. The material integration between the inflatable and knitted elements is a step forward in rethinking the assembly of a material system in which constituent parts are dynamic and perform synergistically. Meanwhile, projects such as “Pneuma-Technics” [10] and “Modular Pneu-Façade System” [11] focus on the actuator itself. The difference in its size, shape, and internal channel geometry produces variations in its elasticity and, therefore, its directional deformation.

“Pneuma-Technics” offers a surface made of soft pneumatic components that can respond and adapt to modulate the passage of light, air, or view. The result is a soft, panelized surface that can open and close through its inflation and deflation patterns. This is similar to Park’s “Modular Pneu-Façade System,” imagined as “a dynamic pneumatic interface which can be used in building applications including responsive façade, ceiling, floor and interior screen, etc.” [12] The strong analogy this artificial system makes to our body’s cardiovascular system and other biological systems, like muscular hydrostats, underscores architects’ fascination with ‘living’ and sentient systems and our strong impulse to tap into their potential for adaptive design. Comprised of modules equipped with sensor, actuator, and control components, the surface can respond kinetically and interact with its environment. It utilizes capacitive sensors and conductive gel, which make it sensitive and responsive to human touch. This layer of soft inflatable elements can be integrated into building skins to make them transformable and active.

Similar to this set of projects, Soft Kinetics utilizes small scale inflatable elements. It focuses on “cellular” pneu structures to achieve its surface dynamics by integrating many inflatable muscles into a component-based surface, forming a self-supporting, pliable, and kinetic “programmable” building skin system. The goal of the project is to engage active structures (inflatable muscles) as ingredients of space-making by exploiting their ability to transform and their capacity to seamlessly integrate into a modular structure.

KINETIC PERFORMANCE: PNEU

Most early experiments in inflatable architecture focused on the structural characteristics of air, but Frei Otto’s research on pneu structures went beyond inhabitation to include pneu structures’ capacity to produce motion. As an effective structural system as well as an instrument of form-giving, pneu structures are abundant in nature.[13] Every cell is itself a pneu structure [14] with air or liquid surrounded by a membrane in tension. In the 1970s, Frei Otto, in collaboration with architects, engineers, biologists, and zoologists, investigated how biological models could influence engineered systems.[15] One result of this effort was extensive research on pneu, its occurrences, forms, and types in nature: membranes of the animal and plant worlds; liquid membranes found in water drops or soap bubbles; the "packed compound forms" of multi-cellular pneus.[16] Pneumatic motion systems were also studied for their potential as adaptable kinetic structures. Their elastic membrane enables a dynamic response to any change in pressure by adjusting mass or volume. This can cause considerable physical transformation of the structure itself, producing a kinetic effect in its own structure and even in adjoining structures. Their soft movement, performed at varying speeds and degrees of freedom, produces a lifelike effect more familiar to the human body. In engineering, rigid materials are employed to fabricate precise and predictable dynamic systems, but natural systems often exceed this performance with their soft and flexible bodies.[17] Most dynamic systems in architecture are based on motors or hydraulics, employing rigid components and mechanical systems of motion; the non-mechanical actuation of pneu structures is a possible substitute for these complex mechanical components.

In soft robotics, the pneu-like capacity is used to move robots by manipulating inflation and deflation patterns. Their "bodies" are capable of large-scale deformation and a high level of compliance.[18] Some of these robots can move around obstacles or squeeze under them. Research by Harvard's Biodesign Lab and the soft robot fabrication techniques described by Andrew D. Marchese et al.[19] provided a starting point for the initial studies of pneu elements used in this project, particularly in the area of muscle fabrication techniques such as the lost wax casting and lamination casting methods. Other relevant research has studied the nature of the soft actuator's movement and motion patterns,[20] and the complexity of this movement.[21] Together, this background demonstrated that the behavior of soft robotic actuators directly relate to their capacity to affect the larger structures into which they are incorporated. This feature was critical to the movement achieved by Soft Kinetics prototypes, a study which gradually improved upon the efficacy of muscle morphology by testing different fabrication techniques and manipulating variables like the muscles' shape, flexibility, and elasticity.

INTEGRATING STABILITY AND KINETICS

Soft Kinetics produces a self-supporting, pliable, and kinetic light modular structure by scaling down to components, softening movement, and using a kit-of-parts logic. It brings together two strategies for designing integrated and adaptive architectural skins: one is concerned with the combinatorial variability of a light structure built by aggregating small components; and the other focuses on the integration and distribution of pneumatic muscles within the aggregated structure. Particular attention was placed on producing a modulated stability, that is, producing a system that maintains its self-supporting capacity while transitioning from rigid to pliable and facilitating kinetics. This was achieved by integrating self-similar components, some of them bendable, with pneumatic muscles producing a "programmable" surface that can open, close, or alter its basic form.

Hard Body of the Modular Structure

These self-similar components that make up the light modular structure of Soft Kinetics are aggregated in a non-orthogonal alignment and can be organized in various configurations. The composition is governed by requirements for stability (self-support) and kinetics, both of which are equally important to facilitate dynamic transformations. In addition to the patterns of aggregation, stability is achieved by interlocking the components through simple slot-friction connections. The kinetic behavior is enabled by a system of pneumatic muscles, their seamless integration with the patterns of aggregation, and the capacity of the modular structure to allow for disruptions in pattern continuity without compromising the construct's stability. The redundancy of connections and elements provides for this structural resiliency.
The structure can be built in a variety of configurations using an 'X'-shaped component and adapted to a variety of spaces. Due to the standardized unit shape and connection, there is great combinatorial potential for assembling the structure. On a local scale, however, the assembly pattern is contingent on the shape of the unit and the angle of its connections. At the same time any slight change in the assembly pattern produces a variation in stiffness where rigid (self-supporting) and pliant (flexible) regions are constructed using the same component (Fig. 2).

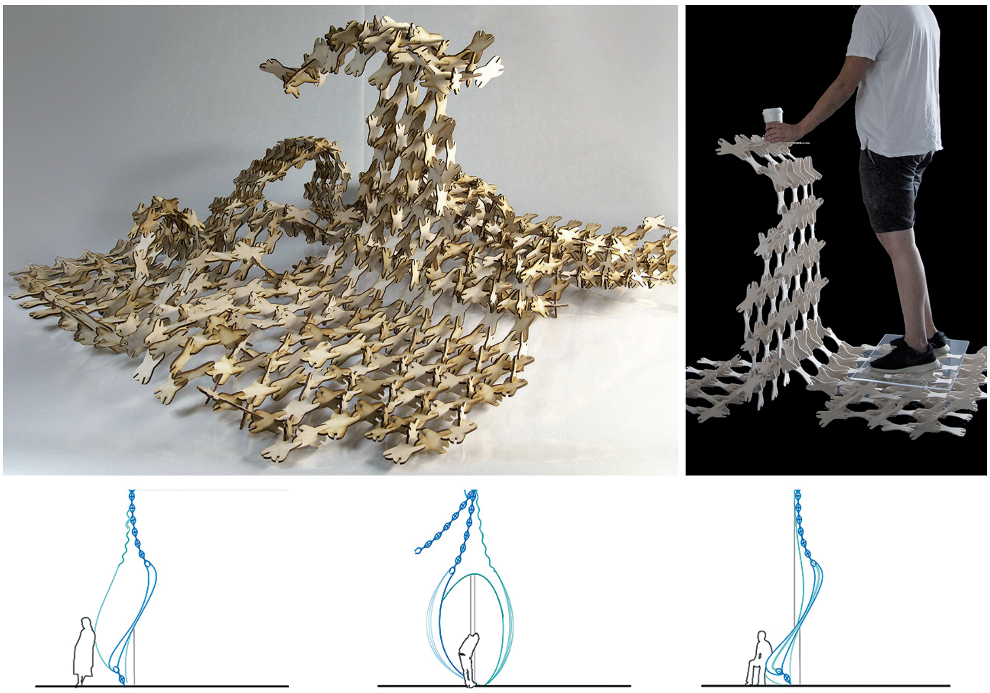

Figure 2. Pliant aggregation can change its configuration when activated while rigid aggregation can serve as a structural support.

Individual components could form any number of permutations, but discrete assemblies, used to govern the form of a larger construct, were generated to support change in functionality, directionality, and form. These discrete physical assemblies were then combined into larger formations in an attempt to examine their tectonic and spatial capacities. However, due to its combinatorial potential, the system itself remains open and able to adjust to a variety of spatial/contextual conditions, supporting individual part replacement. In this way, recalibration of the construct can be maintained since its parts can be disassembled or reconfigured in a variety of ways (Fig. 3).

The component shape was chosen for its capacity to produce a significant number of different combinations while maintaining a pattern that generates rigid and pliant versions. These configurations were then modeled digitally and tested physically for their behavior. To support transitions between rigid and kinetic regions of the structure, a new bendable component was designed. These components, identical in shape to their rigid counterparts, were engraved with a laser cut pattern that made them flexible. The bendable units were positioned adjacent to pneumatic muscles to facilitate the bending of regions where active muscles were placed. Ultimately, the light modular structure could negotiate changes in direction (straight, angled, curved), thickness (from a surface to a three-dimensional construct, through layering), and structural capacity (from self-supporting to bendable and kinetic). All of this was achieved with a simple kit of parts consisting of rigid and flexible same-shape components.

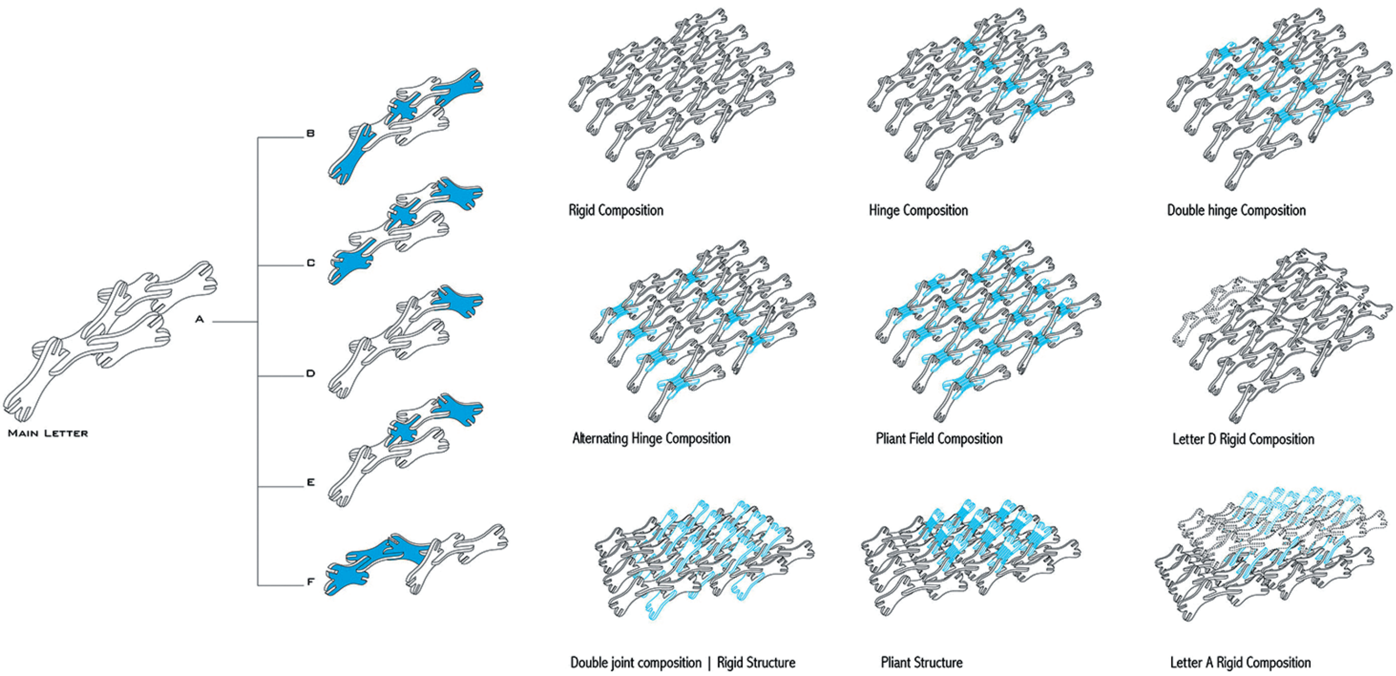

Figure 3. Just a slight change in the position of the component can change topography of the surface while bendable component seen in blue ensures a pliability of the segment.

Kinetic Typologies of Pneumatic Muscles

The soft body of the Soft Kinetics project consists of a continuous and interrelated network of clustered groups of pneumatic muscles. Within a group, the muscles are linked by silicone tubes that allow the passage of air to inflate and deflate them in a sequence. When activated, these clusters move entire regions of the modular structure, producing apertures that open and close. (See Fig. 1.)

The movement of pneumatic muscles depends on the flexibility of the elastic material, the volume of internal chambers, and their geometry.[22] Marchese et al. list three soft robot morphologies differentiated by their internal channel structure: ribbed, cylindrical, and pleated.[23] The soft body components of the actuation system would be classified under the ribbed muscle morphology. Its internal channels are produced using two different techniques: lost wax casting, and a combination of lamination casting and soft lithography fabrication methods. Respectively, these two techniques resulted in two muscle types: the central channel muscles (S, V, and B) and the distributed channel muscle (M). (Fig. 4.) The fabrication technique defines elasticity and inner channel geometry that directly influence the amplitude and degree of muscle movement, instrumental in generating desired effects.

The range of behavior of designed pneumatic muscles was explored through prototyping and iterative design, their performance observed before and after integration within a modular structure. Their position within this

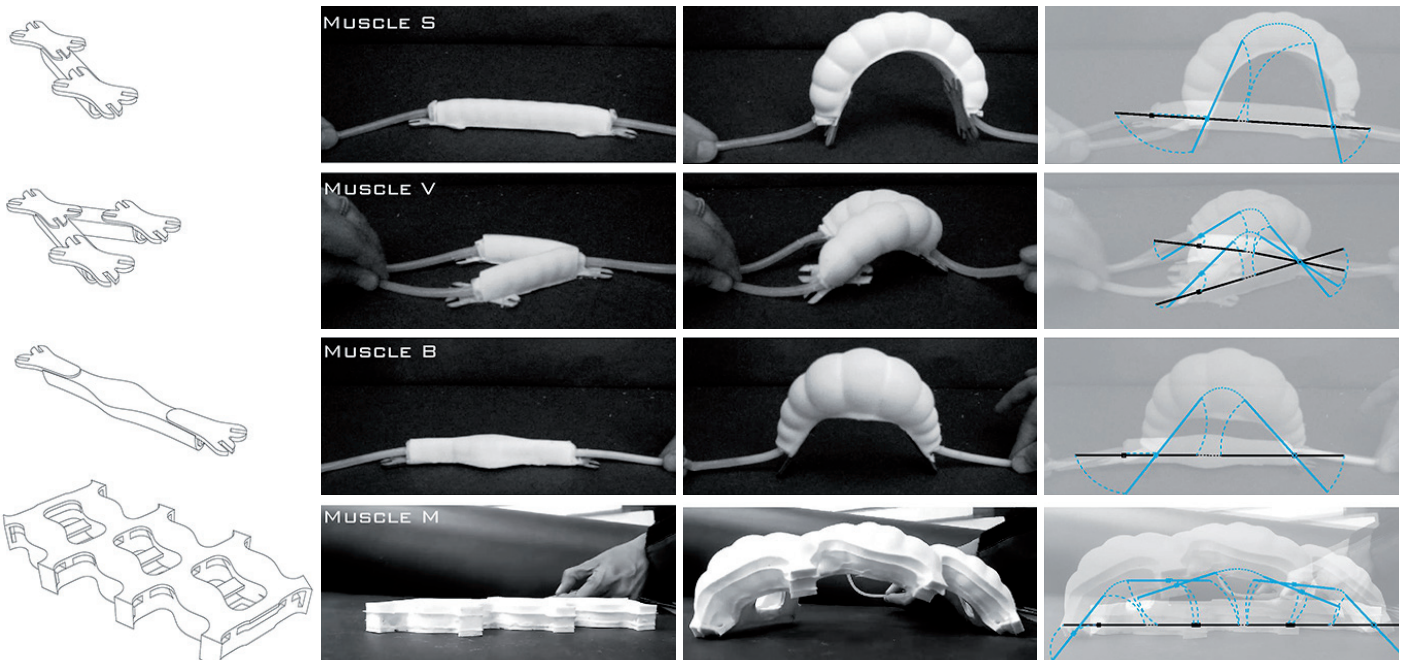

Figure 4. Muscle performance diagram describes muscles' behavior and deformation amplitude.

modular system determined their length and size. Muscles S and V were designed to integrate into the assembly grid pattern and be exchanged with the hard components of the modular structure continuing its pattern; muscle B was designed to allow for omission of the hard components and to support interruptions of the grid pattern by nesting within the created voids and bridging the interruption; muscle M was designed to wrap around existing grid components, filling the voids of the grid with its inflatable parts (Fig. 5). These rules of placement determined the muscles' overall shape, technique of production, and, therefore, kinetic typology. The central channel muscles (S, V, and B) produced using the lost wax technique acted along their long axis similar to a linear actuator, exhibiting significant bending along that axis. The distributed channel muscle M, having the larger area, did not exhibit robust bending, but instead demonstrated a capacity to act along the wider area as a form of dynamic hinge. (See Fig. 4.)

Integration and Prototypes

The soft body of pneumatic muscles was integrated with the hard body of the light modular structure, their seamless connection achieved by fusing a single modular unit to the ends of the central channel muscles (S, V and B), and by enabling the distributed channel muscle (M) to fit within the voids of the gridded modular structure. (See Fig. 5.)
Fusing a modular component to the central channel muscles enabled a consistent, slip-joint connection between the hard and soft parts of the modular system. The S, V, and B muscles were integrated into the hard body of the structure just like any other modular component of the

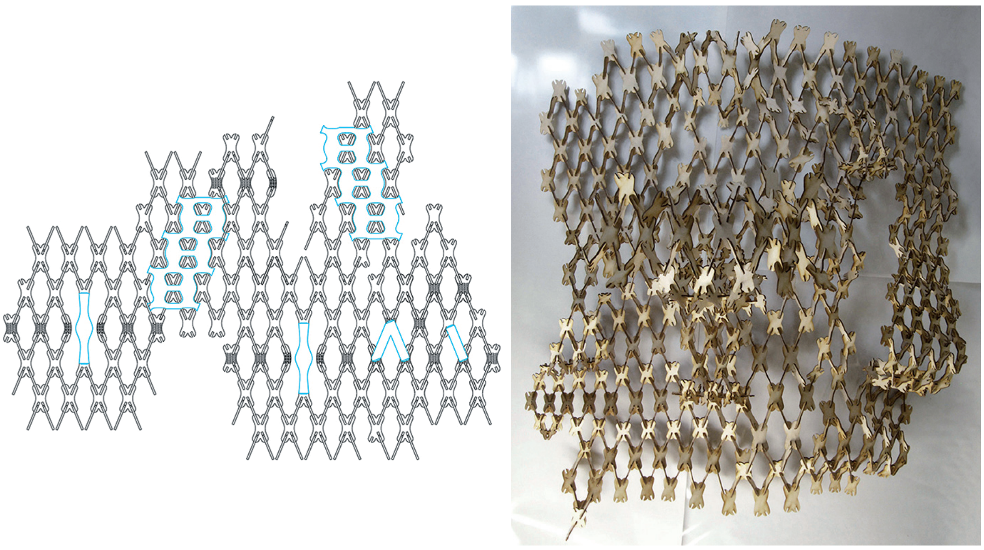

Figure 5. The "soft" body of pneumatic muscles and the "hard" body of the light modular structure are integrated in three ways: by replacing the standard (hard) components of the grid pattern, by allowing interruptions of the grid pattern, and by nesting the components within the grid voids.

system, while the M muscle was wrapped around the existing structure. (See Fig. 6.) The soft pneumatic muscles could be interchangeable with hard components and positioned to displace the hard parts of the modular structure creating interruptions in rigidity. Meanwhile, another of the soft muscles (M) could be enveloped around any region of the structure to produce active displacement. The combined effect allows the soft body to perform in a way similar to an active connective tissue while still maintaining the overall assembly pattern of the structure. This strategy supports muscle distribution throughout the structure in a number of ways; concentrated in some areas and placed sporadically in others, while always preserving the overall structural integrity of the larger structure. This is seen as a very promising direction to be further explored in future phases of the project.

Several small prototypes were constructed to test various combinations of muscle integration. It is in these prototypes that the clustering of muscles was explored. The clusters, consisting of three to five pneumatic muscles, were inflated in sequence. Solenoid valves controlled the inflation and deflation pattern (supply and exhaust) and their work was regulated through an Arduino microcontroller. The rate and duration at which valves opened and closed was set to allow all linked muscles to inflate in sequence; the pressure was controlled through a sensor to prevent over-inflation and damage to the muscles. Muscles linked in a cluster worked as a group, affecting dynamically a targeted region of the structure. The work of the soft body that opens and closes apertures could either be controlled through proximity sensors making the construct responsive to changing external and internal conditions, or be regulated by light sensors to serve as a functioning shading device.

RESULTS AND DISCUSSION

A kit-of-parts logic was essential to achieve the tectonic integration of stable and kinetic elements into a unified system. There are three basic components that comprise this system:

(1) an ‘X’-shaped basic rigid component made from plywood and used to form a hard body,
(2) an ‘X’-shaped bendable component also made from plywood and engraved with a laser cut pattern used to form flexible regions of the system, and
(3) inflatable silicon muscles used to form a soft body.

These three elements were used interchangeably to make up a dynamic material system that supports multiple spatial and dynamic configurations. The research so far shows that this is a promising way to integrate an active pneumatic layer within a light modular structure.
The range in the structure’s properties from rigid/stable (self-supporting)

to pliable/active (dynamic) was made possible through a pattern of aggregation that was a direct product of the size and geometry of the component. The system of aggregation of the original component and its resultant grid determined the dimensions and shapes of the inflatable components. The reliance on the grid made the interchangeability of all components possible; the extensive combinatorial capacity of the aggregation assembly pattern produced a structure that could be at the same time self-supporting, pliable, and kinetic.

The kinetic behavior is facilitated by four different muscles, distinguished by their size and the techniques used in their production. Both central and distributed channel muscle types had ribbed inner chambers, but a difference in their production technique generated a difference in wall thickness and air channel volume among the muscles. The central channel muscles were produced using a CNC-milled mold and lost wax casting technique: this technique formed small divisions between the muscle's air chambers that corresponded to the overall narrow and elongated shape of the muscle. The resultant walls were relatively thin, allowing for larger expansion of the muscle (and more significant deformation) when inflated. The distributed channel muscle was made using a mold produced by laminating laser cut acrylic material. This technique allowed for the formation of larger divisions within the air chamber of the muscle, again corresponding to the latter's overall shape. The thicker walls of this muscle

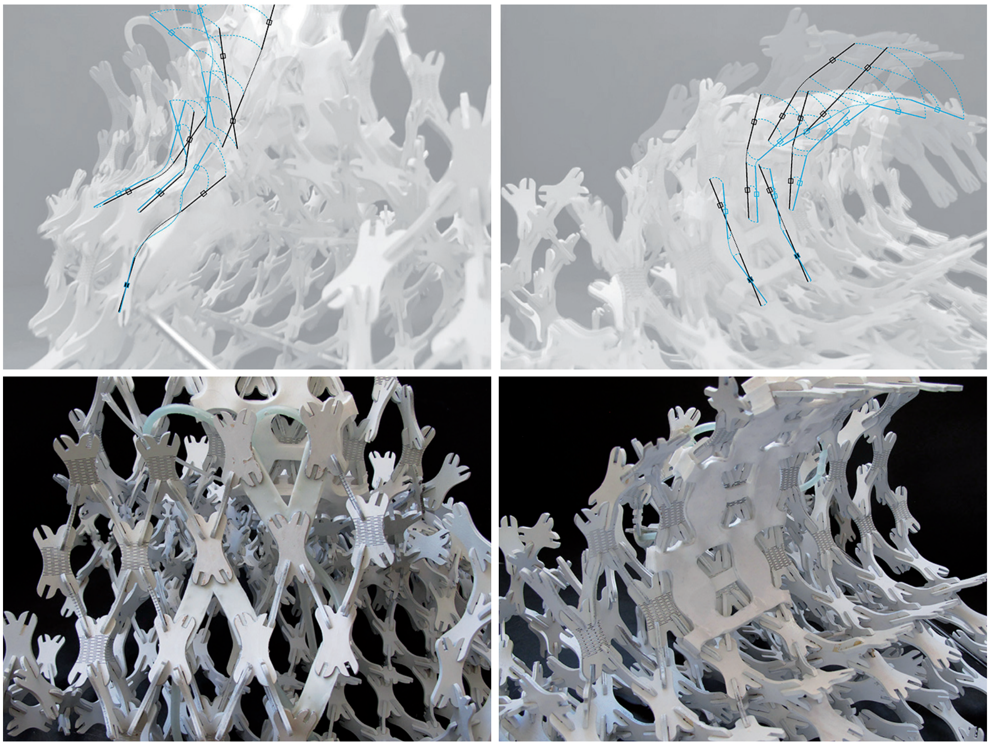

Figure 6. “Pneus” performance diagram: muscle V cluster and muscle M wrapped around standard structure components.

limited its expansion. Though it experienced less deformation, compared to the central channel muscles (S, B, and V), this muscle type (M) generated considerably greater power when pulling elements attached to it, resulting in a more robust deformation of the surface regions where it was deployed.

Soft elastomer pneumatic muscles are capable of continuous deformation, but the challenge here was to isolate a particular bending movement within its length.[24] To direct their motion, one side was fabric-reinforced to limit elasticity and control inflation. Projects like the "Pneuma-Technics" [25] and the "Modular Pneu-Façade" system [26] focused predominantly on the design of soft inflatable components. The extensive study in "Pneuma-Technics" of muscle movement in relation to their shape and size informed the Soft Kinetics project. The modularity of Park's "Modular Pneu-Façade" system's inflatable elements resulted in a continuous soft inflatable surface and influenced the idea of a continuous soft body in Soft Kinetics. PneumaKnit's intent to integrate different material constraints of inflatable components and its knitted layer informed the underlying idea of tectonic integration explored in the Soft Kinetics project. However, the Soft Kinetics project takes further the integration of its soft inflatable layer into a larger material system, achieving this integration through an interchangeable system of soft and hard modules. The actuation system (soft body) in Soft Kinetics is not seen only as a means to achieve dynamics: it has a role of providing material continuity and connections among all modular elements (soft and hard) while also making regions of the system dynamic and acting as a connective tissue.

In nature, functionality and materiality of systems are integrated. Natural material systems generate movement and force through an interaction of materials, structures, energy sources, and sensors.[27] Furthermore, these systems do not distinguish between structural and functional materials: both travel through integrated material layers and inform material distribution within the organism. Naturally constructed material systems have a hierarchical structure on many levels that span several orders of magnitude.[28] Functional properties of these materials can vary and change from one structural hierarchical level to the next, producing variability that can adjust to and accommodate changes in the environment. Manmade material systems tend to distinguish between functional and structural aspects of the material: they are constructed, assembled, and designed to respond to a specific design and performance criteria by separating functional and structural aspects of the system. This project attempts to integrate those capacities within an architectural assembly, by integrating functionality and materiality of soft/dynamic and hard/structural layers to produce dynamic architectural assemblies.
Even though Soft Kinetics achieves the integration of soft active elements, more research is necessary to define the limits of the kinetic performance of pneu-structures. The integration of actuators within the aggregation pattern of the structure allows for movement of its regions. In the current

study, small clusters of actuators and their behavior were examined. Their distribution within the structure's aggregation pattern needs further study to fully understand the potential of this system to move larger regions of a structure. New computational tools for simulation of complex non-elastic behavior will be employed so that alternate designs can be quickly tested. Future research will also focus on the design of alternate aggregation patterns to further experiment with the range and amplitude of motions.

This project was developed as a proof of concept. Therefore, its scale and materiality need to be further explored. Structural analysis of the system also needs to be conducted since the current project's structural viability was confirmed only through observations and testing of scale models. Building significantly larger models is necessary to enable further development of the kinetic typologies of the system and to understand the complex relationships between multiple movable regions. Material choice for scaling up hard elements of the system is one of the significant challenges since lightness of the modular system will be important for successful future development. Therefore, more research is required to define the "blended" materiality of the modular structure, as well as the durability and weight of the embedded pneumatic components. The structure is currently made of plywood, but the use of aluminum, plastic, and woven carbon fiber will be explored in future iterations.

Nevertheless, this research demonstrated that, as a form of material actuation, the pneu structures are capable to produce dynamic effects when integrated into larger structures. This implies that an actuation system based on pneu elements could reduce the use of complex mechanical systems usually present in dynamic architectural assemblies (e.g., dynamic building facades). Conceiving the soft actuation elements as modular parts of the larger system made their integration possible. It also contributed to the production of a uniform material system that can be built in a variety of configurations. Architecture as a discipline is confronted with the challenges of the climate crisis and has a responsibility not only to design sustainable buildings, but to also articulate the ways in which it participates in processes of environmental transformation. Whether it is the climate, energy, or human pressures, buildings are increasingly expected to actively respond to these forces and their mutable nature. The work presented here is an attempt to address those urgent challenges by exploring adaptive envelope solutions as agents of dynamic exchange between the interior and exterior.

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Credits

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