Complexity Biomechanics:

A Case Study of Dragonfly Wing Design from Constituting Composite Material to Higher Structural Levels

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Abstract

Presenting a novel framework for sustainable and regenerative design and development is a fundamental future need. Here we argue that a new framework, referred to as Complexity Biomechanics, that can be used for holistic analysis and understanding of natural mechanical systems is key to fulfilling this need. We also present a roadmap for the design and development of intelligent and complex engineering materials, mechanisms, structures, systems, and processes capable of automatic adaptation and self-organization in response to ever-changing environments. We apply Complexity Biomechanics to elucidate how the different structural components of a complex biological system as dragonfly wings, from ultrastructure of the cuticle, the constituting bio-composite material of the wing, to higher structural levels, collaboratively contribute to the functionality of the entire wing system. This framework not only proposes a paradigm shift in understanding and drawing inspiration from natural systems but also holds potential applications in various domains, including materials science and engineering, biomechanics, biomimetics, bionics, and engineering biology.

Keywords: Complexity theory, biological composites, cuticle, collective intelligence, holistic biomimetics.

Introduction

Nature hosts a diverse array of creatures. Each resilient survivor in nature is a potential source of data, which can be the raw material for our information, knowledge, understanding, and wisdom [1]. As we observe the natural world, draw inspiration from it, and derive solutions in order to gain deeper insights into our planet, address industrial challenges, and confront global issues, the first conspicuous feature is complexity [2]. According to the Cambridge dictionary, *'complexity' is the state of having many parts and being difficult to understand or find an answer to.* This precisely characterizes what we encounter in numerous natural systems across various scales and levels of organization.

To unravel the intricate nature of complex systems, scientists have increasingly turned to a reductionist approach. This approach involves breaking down natural systems into comprehensible physical components and phenomena. While the reductionist approach has successfully answered numerous scientific questions, it falls short in scenarios, such as chaotic systems, insect swarms, bird flocks in flight, insect combat behaviors, ant social networks, human brain neural networks, and various other cases. In these instances, the reductionist approach proves inefficient due to the inherent unpredictability, interdependencies, and interconnectedness of the examples mentioned [3]. In these cases, complexity theory is the key to explain how such systems work [4]. Complexity theory helps us understand how the collective behaviors and properties of complex systems emerge from the interactions of seemingly independent elements. These elements collaborate to form, grow, learn, adapt, and evolve the entire system [4-8]. Consequently, complexity theory can facilitate our understanding of the social and collective behaviors exhibited by complex natural creatures.

When we approach nature from an engineering perspective and focus on the mechanical design of natural systems, we uncover collective mechanical behaviors and emergent mechanical properties resulting from their specialized design. For example, observations of snake locomotion systems [9-11], fish body armors [12-14], gecko adhesive pads [15-18], insect flight systems [19-24], beetles fighting mechanisms [25,26], and many more indicate that natural mechanical systems consist of complicated material composition, nano- and micro-architecture, and structural elements. This complicatedness can arise from two underlying design principles: (1) a network of simple design elements that collectively form a complex system, and/or (2) a collection of complicated subsystems that together constitute the entire system. Here, the 'simple design element' denotes the most elementary building block within a mechanical system, while a 'complicated subsystem' refers to a more intricate design element characterized by numerous design details. These design principles give rise to 'complex mechanical systems,' which, in turn, yield complex mechanical functions, collective mechanical behaviors, and emergent mechanical properties.

A striking example of such complex mechanical systems can be found in wings of dragonflies. The wings comprise numerous simple design elements and complicated subsystems, ranging from the material composition and ultrastructure to larger structural components, all collaborating as part of a complex network system. Thanks to their specialized wing design, dragonflies have become one of the most proficient flyers with ~97% hunting success rate [27]. These agile insects can spontaneously change their directions in flight [28,29], and further display an array of flight behaviors and long-distance flights across oceans with minimal energy consumption [30-32]. However, a puzzling question remains: how do dragonfly wings enable such sophisticated flight capabilities, especially considering they lack any musculature within their wings?

One of the key reasons behind the flight ability of dragonflies is the automatic deformability and the flapping modes of their wings, which results in a variety of flight modes (i.e., flapping, hovering, gliding, etc.) and high maneuverability. The principal function of the wings is to generate aerodynamic forces. That is when emergent mechanical properties and collective mechanical behaviors arise from interactions between wing material and structural elements. To understand the complexities, emergent mechanical properties and collective mechanical behaviors of natural mechanical systems, including the automatic deformability of dragonfly wings, we introduce a novel framework, called "Complexity Biomechanics." This framework is rooted in complexity theory and is applied to dragonfly wings as a prime example. In doing so, we present a roadmap for the future of engineering design, utilizing the Complexity Biomechanics framework, which is essential as it enables us to push the boundaries of engineering design to align more closely with the designs found in nature, taking a holistic approach.

Complexity Biomechanics in dragonfly wings

In this section, we first elucidate the concept of the Complexity Biomechanics framework and how it enables us to better understand and interpret how the dragonfly wings work. According to

Complexity Biomechanics, simple and/or complicated design elements of a natural mechanical system come together to form an interconnected and interdependent complex network system. This network system exhibits collective mechanical effects that surpass the combined impacts of individual elements. These emergent properties result from several characteristics of the system: (1) synergistic relations between the design elements, including material and structural elements, (2) sensitivity of mechanical behavior to boundary conditions and loading scenarios, (3) non-linearity in geometry, material, and contact, along with non-linearity in boundary conditions and loading scenarios, (4) sensitivity of mechanical behavior to initial design parameters, (5) continuous adaptation in response to unpredictable loading scenarios in volatile and ever-changing environments, which leads to (6) self-organization of the whole system without a necessity for a central control system. In the following, we will explore the specific design elements present in dragonfly wings and illustrate how their interactions give rise to collective mechanical behaviors and emergent mechanical properties.

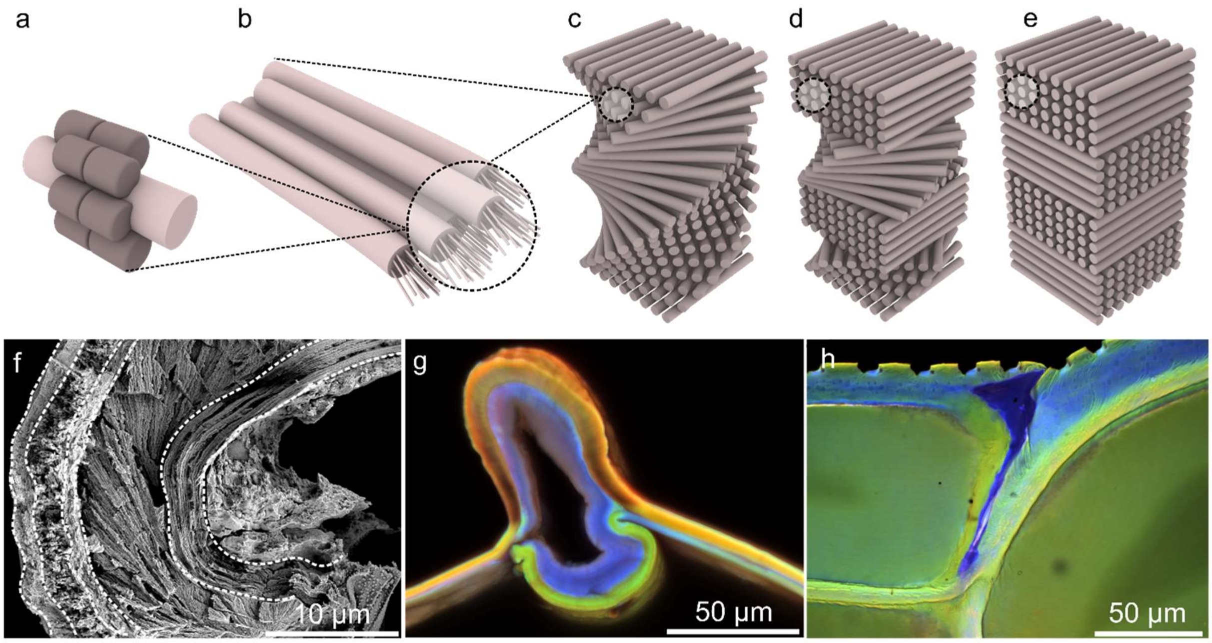

Figure 1. Micro-architectural design of the dragonfly wings' cuticle. (a) Chitin nanofibrils wrapped with proteins. (b) Chitin-protein fibers in protein matrix. (c-e) Different arrangement of chitin-protein planes. (f) Micro-architecture of the wing veins cuticle consisting of six distinguishable cuticle layers. (g) Confocal Laser Scanning Microscopy (CLSM) image of the cross-section of the veins showing different levels of sclerotization: Red, green, and blue colors are indicators of sclerotized cuticle, less-

sclerotized cuticle, and soft cuticle, respectively. (h) CLSM image showing the presence of soft cuticle, i.e., resilin, in nodus. The panels a and b are inspired by [61]; The panel f is reproduced from [35]; The panel g is reproduced from [47]; And, the panel h is reproduced from [42].

Dragonfly wings exhibit complicated mechanical design, ranging from the smallest elements of their constituting composite material, i.e., cuticle, to the entire wing structure. These wings must strike a balance between stiffness to prevent detrimental deformations and flexibility to generate flight forces. These mutually exclusive properties of the wings are made possible through several design strategies.

The primary material of dragonfly wings is cuticle, a biological composite material primarily composed of chitin nano- and microfibrils embedded within a protein matrix (**Fig. 1 a,b**). Chitin microfibrils, in their pure form, have a stiffness of approximately 150 GPa [33]. The arrangement of these microfibrils varies depending on the specific cuticle layer (**Fig. 1 c-f**).

Dragonfly wings have a complex layered architecture. Veins, for example, consist of up to six cuticle layers, which vary in their ultrastructure (**Fig. 1 f**) [34]. These layers may or may not be present in other veins, depending on their location in the wing [34, 35]. The number of layers is also different in the wing membrane, which usually consists of three cuticle layers only [34, 36]. The mechanical properties of the wing cuticle are influenced by the arrangements of the microfibrils and other factors, such as chemical composition, sclerotization, hydration level, and porosity, resulting in a wide range of properties, from high stiffness to extreme flexibility in this biological composite (**Fig. 1 g, h**) [33].

In a structural level, wings feature a corrugated structure, supported by a complex network of veins. Cross veins are linked to robust, span-wise longitudinal veins by vein micro joints. This design provides the wings with notable rigidity against span-wise forces while allowing flexibility in the chord-wise direction. Additionally, other design elements, such as resilin-rich flexible joints, fused joints, spikes, spike-containing joints, nodus, basal complex, pterostigma, and flexion lines together create a complex network, enabling the wing to achieve the necessary camber and twisting for aerodynamic force generation during flight (**Fig. 2**) [37-41]. These elements not only establish synergistic relations, operating as a mutually dependent and interconnected wing structure, but also exhibit mechanical responsiveness influenced by their initial design factors.

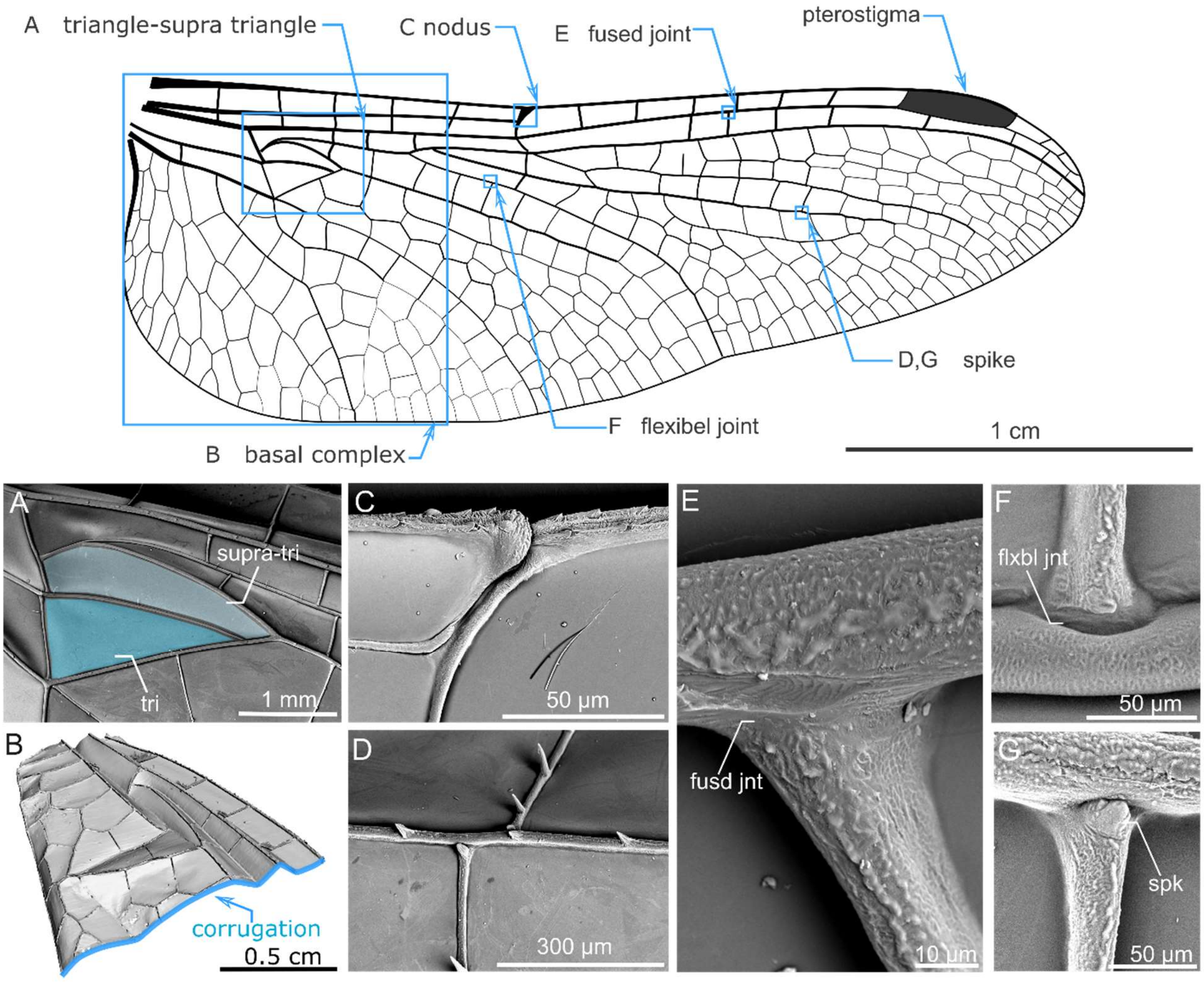

Figure 2. Dragonfly's wing and its design elements. Triangle (tri) and supra-triangle (supra-tri) (A), basal complex and corrugation from the fore wing (B), nodus (C), spikes (D), fused joint (fusd jnt) (E), flexible joint (flxbl jnt) (F), spike-containing joint (spk) (G). The panel A is reproduced from [43]. The panel B image is reproduced from [41]. The panels C and D images are reproduced from [47]. The panels E, F, and G images are reproduced from [37].

The variation of these design parameters in dragonfly wings leads to distinct mechanical adaptations to the forces encountered during insect flapping flights. In typical or challenging scenarios, such as flying in windy and rainy conditions for hunting, dragonflies' wings experience continuous changes in boundary conditions and loading scenarios. These variations depend on factors like flight direction and flapping modes. To successfully hunt other insects, the dragonfly must continually adjust its flapping wings to unpredictable external and internal loading scenarios. The simple and complicated elements of dragonfly wings collaborate passively, forming a selforganizing system that emerges from the wings' continuous adaptability. Despite generating flight forces through active muscles at the flapping wings' base, the wings' deformability primarily occurs mostly in an automatic way without centralized control systems dictating their shape. This wing response, which includes automatic shape changes, is the emergent complex mechanical behavior of the wings [42-44].

The emergent complex mechanical behavior of the wings is the result of non-linear interactions between all elements of the wing network, which originates from the different sources of non-linearity, i.e., geometric non-linearity (e.g., symmetric or asymmetric corrugations, and the pre-cambered cross-section of the wing), material non-linearity (e.g., in different arrangement of chitin microfibrils, and in resilin patches as a hyper-elastic material), and contact non-linearity (especially in spike-containing joints, and nodus). The mechanical interactions between the network of design elements as well as the associated non-linearities can be viewed as a network of distributed information processing, a process called mechanical computing [45]. This form of mechanical computation or information processing can not only be regarded as a material property [45] but also as an intelligent structural property of the entire wing system.

Dragonfly wings often encounter collisions with objects in their environment, which can lead to flight instability and wing damage [46, 47]. To overcome these issues, some emergent mechanical properties and collective mechanical behaviors of the wings come into play. The damping property of the wings enables the dragonflies to maintain their flight stability, which is the result of the interplay between the complex network of resilin-rich flexible joints and hinges with other parts of the wing [46]. Damage resistance of the wing is an outstanding example of emergent mechanical properties of the wing, protecting the wings during accidental collisions, which results from the flexibility of the material of wings caused by some specific areas of elasticity, i.e., resilin-rich areas [48]. Although wings are damage resistant, in some extreme cases they may still undergo damage, leading to wing area loss. Surprisingly, when damage occurs, another damage-mitigating property emerges, which is the by-product of the presence of cross veins. Cross veins function as barriers against crack propagation and, therefore, mitigate damage progression [49-51]. Another extraordinary emergent property within the dragonfly's flight mechanism arises in the aftermath of wing damage – it compensates for the loss of wing area by increasing flapping frequency and/or amplitude [46,47]. This adaptive change in the flapping frequency and/or amplitude underscores the complex nature of the entire flapping system, demonstrating its ability to dynamically respond to new and unpredictable scenarios. It is crucial to note that the adjustment in flapping frequency can be understood as an active response involving neuronal cellular sensing, neural circuit steering, and direct flight musculature engagement.

Taken together, the narrative reveals the emergence of "collective intelligence" within dragonfly flapping system, spanning multiple levels of organization, from a material level and small-scale architecture to large scale structural design elements. This collective intelligence empowers the insect to continually adapt to novel and unforeseen loading scenarios, serving as a remarkable example of mechanical intelligence (MI) in nature [52], where a biological system, here the insect flapping system, responds to environmental stimuli mostly in a passive-automatic way, though some active responses are also involved.

A roadmap to holistic biomimetics

Complexity Biomechanics offers a holistic perspective for synthesizing the information acquired through a reductionist approach. This enhances our interpretation and understanding of the physical working principles, complex mechanical behaviors, functions, and emergent properties of the system under investigation, in this case the insect wings. This understanding extends beyond the wings alone, encompassing the insect's behavior and its dynamic interaction with the environment. Yet, a question remains: How does Complexity Biomechanics contribute to the development of a holistic biomimetic framework?

The answer lies in recognizing the system under study as an integral part of an organism engaged in continuous interaction with its ever-changing environment (**Fig**. **3**). This paradigm shift allows us to transcend the confines of reductionism, opening avenues for a more integrative and holistic approach to biomimetics, where the intricate interplay between biological systems and their surroundings is considered in the design and development process.

To achieve a holistic biomimetic framework, there is a need to revolutionize the current biomimetic framework. This transformation can be achieved by aligning engineering designs as closely as possible with the successful design solutions found in nature, which inherently possess the capability for continuous adaptation. To tackle this goal, a reductionist approach to clarify design principles (**Box. 1**), a holistic view of natural mechanical systems, holistic design imitations, and holistic manufacturing systems are needed (**Fig. 3**). The first step involves understanding the natural system at various hierarchical levels, from material level to higher structural level and the entire network system, and how it interacts with the environment. Then, the results of the exploration can be used to provide insights into how the systems contribute to essential functions and behaviors of an organism, and its dependence on environmental interactions for survival (see **Fig. 3**). To achieve this, new mathematical methods including the Bayesian mechanics [53] are needed that can model, quantify, and predict the interdependencies, interconnectedness, and complex interactions between the design elements of the systems.

With this data, it becomes possible to adopt a holistic view to interpret and comprehend the complexities of natural mechanical systems. Complexity Biomechanics, along with its principles, may serve as the linchpin to achieve this holistic perspective, ultimately enabling the creation of engineering designs that truly mimic natural systems and their interactions with the environment. This entails the incorporation of all initial design parameters, boundary conditions, loading scenarios, and nonlinearities derived from the interactions of the system with the environment. For example, in the case of flapping wing systems, holistic understanding not only reveals collective intelligence, emergent properties, and behaviors of the system but also encompasses crucial aspects such as material and structural design, control systems design, and overall functionality of the whole flapping wing.

To this end, it is necessary to develop and utilize a more advanced infrastructure for a holistic manufacturing system, i.e., software, hardware, and manufacturing tools. This includes but is not limited to, generative design, generative artificial intelligence (AI), brain-inspired computing [54], image processing, augmented reality (AR), virtual reality (VR), digital twin, advanced central processing units (CPU), graphics processing units (GPU), hard drives, and random-access memories (RAM) as well as Nvidia Omniverse platform.

For example, to achieve a comprehensive understanding of the design and manufacturing of flapping wing systems, Complexity Biomechanics suggests a multidisciplinary approach, utilizing state-of-the-art technologies mentioned earlier to develop a virtual environment in the immersive Nvidia Omniverse platform. In this virtual platform, generative AI is employed to simulate and generate wing interactions, providing valuable insights into emergent properties and behavioral patterns. Virtual reality and augmented reality technologies are utilized to create immersive environments, enabling the visualization and analysis of the complex dynamics of flapping wings within diverse surroundings. Image processing techniques enhance our ability to extract detailed engineering data, facilitating a deeper understanding of collective intelligence, control systems, material design, and structural complexities. Additionally, virtual environment development serves as a tool for acquiring real-time engineering data to study the dynamic interplay between flapping wings and their environment in a controlled and replicable setting. Advanced 3D and 4D printing technologies, capable of material and structural gradient printing with high precision on a small scale using biodegradable materials, are employed not only to ensure the creation of requisite material properties but also to facilitate easy decomposition in the environment after use.

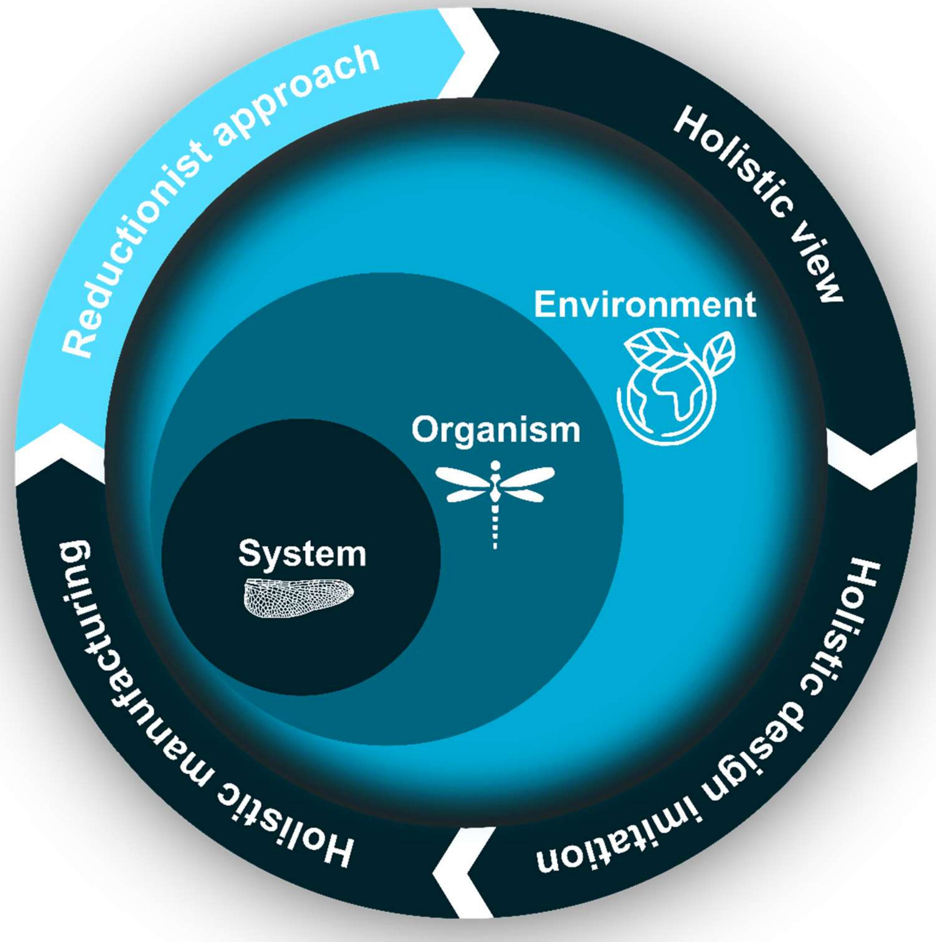

Figure 3. From complexity biomechanics to holistic biomimetics.

Why Complexity Biomechanics?

As stated by Gregory Bateson: "*The major problems of the world are the result of the difference between the way nature works, and the way people think*". For instance, our current engineering frameworks, which predominantly employ reductionist approaches, have contributed to environmental damage, global issues, and other unintended consequences. Therefore, embracing a holistic approach to design and manufacturing becomes imperative to alleviate these negative impacts by harmonizing engineering designs more closely with natural systems.

Complexity Biomechanics is the key to tackle these issues presenting a paradigm shift in our understanding of mechanical systems, especially natural mechanical systems as they show complex mechanical behaviors, complex functions, and emergent mechanical properties. It adopts a holistic approach along with the conventional reductionist approach by incorporating the principles of complexity theory to investigate, analyze, and understand the complexity and emergent properties of mechanical systems found in nature. In addition, Complexity Biomechanics can facilitate the establishment of a holistic engineering design framework through which the underlying design principles of natural systems can be transferred to design and develop bio-inspired complex mechanical systems. These complex mechanical systems can show collective intelligence and, thereby, interact and adapt to their immediate environment, for real-life applications. A few practical applications of Complexity Biomechanics in the design of intelligent systems, matters [55], materials, structures, and processes can be miniaturized flapping robots, autonomous robots, soft robots, intelligent composite materials, and adaptive structures with the ability of automatic shape control.

Albeit here we only demonstrated the application of Complexity Biomechanics in the analysis of the biomechanics of dragonfly wings, the extent of its applicability in biomechanics, biomimetics, biomimicry, bionics, and bio-inspired design can be well-beyond the presented case study. Other areas of science and engineering can take advantage of this novel paradigm to develop a new engineering design framework since the design principles of Complexity Biomechanics are in line with those of sustainable and regenerative design and developments [56]. This can lead to a quantum leap forward in a variety of mechanical and engineering sciences to build a sustainable and even regenerative future for the next industrial revolution.

1 **Box.1**

Bio-inspired applications of complex natural systems: reductionism or holism?

"It's not what you look at that matters, it is what you see."

Henry David Thorea

To address industrial challenges, the utilization of biomimetic engineering applications based on complex natural systems has been significantly growing. This surge is attributed to the rich biological diversity of natural creatures, which serves as a valuable source of inspiration for engineering designs. Despite the intricate functions of many of these creatures, some offer simple yet effective design solutions, making them potential case studies for engineering innovation. An exemplary example of this nature-to-engineering approach is the study of dragonfly wings. In recent years, various design elements from dragonfly wings have been incorporated to create durable bio-inspired kites [57], splints that combine mobility and support [58], dual stiffness origami grippers and impact resistant quadcopters [59], and triple stiffness airplane wings that resist typical flight forces but elastically buckle in collisions [60]. In these applications (**Fig. 4**) researchers have used a reductionist approach for the analysis and modeling of engineering systems. Reductionism, as one of the main principles of engineering disciplines, has been shown to be a highly practical approach. However, in the design of intricate systems aimed at sustainability and regenerative development, comprising numerous diverse, interdependent, and interconnected networks of elements, relying solely on the reductionist approach becomes impractical. This is where Complexity Biomechanics, as an alternative holistic perspective, comes into play. We propose that Complexity Biomechanics represents the future direction for science and engineering disciplines.

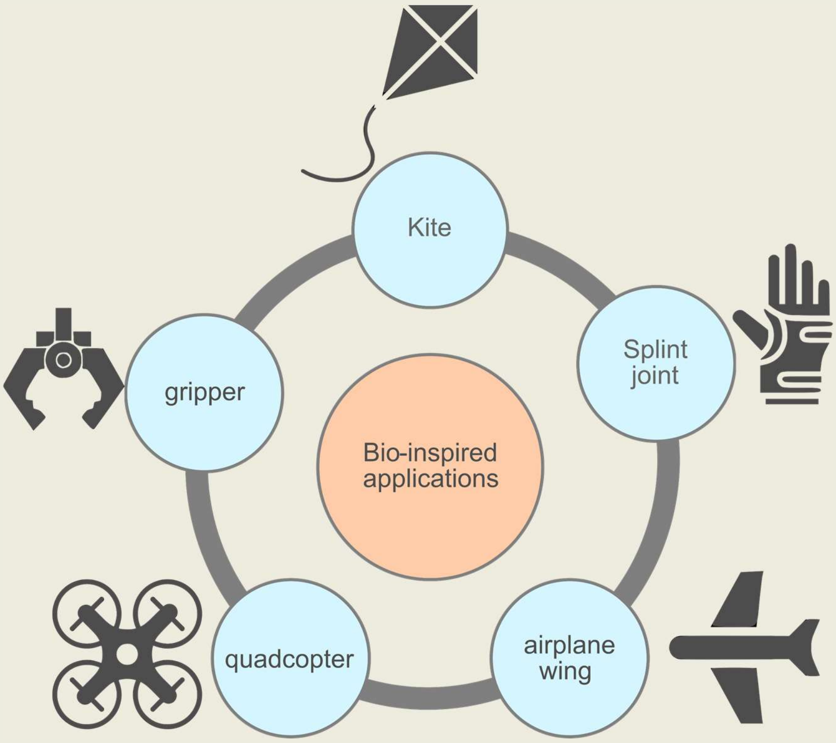

Figure 4. Engineering applications inspired by the structural and material design elements of dragonfly wings, namely bio-inspired kite, splint joint, airplane wing, dual-stiffness origami, and gripper.

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Author contribution

Conceptualization: A.T., S.H.E., H.R.; investigation of concept: A.T., S.H.E.; project administration: A.T., S.H.E.; data resources: H.R.; supervision: A.B., H.R.; visualization: A.T., S.H.E; writing-original draft preparation: A.T., S.H.E.; writing-review & editing: S.H.E., A.B., H.R.

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