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Nature as a Technological Paradigm: The Case of "Moisture-Responsive Wrinkling Dynamic Footwear"

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Abstract: The forces of nature have shaped the form of matter, and similarly, human creations are also driven by natural forces. This makes biology a key source of inspiration for solving engineering problems. With the rapid advancement of digital and robotic technologies, rapid prototyping technology has made it possible to manufacture complex parts, creating a new body of knowledge and a novel approach to design known as generative design. This paper focuses on applying biology and related life science technologies to the paradigm of generative design and how this paradigm influences the concepts, strategies, and practices in the design field. The article also specifically examines the project "Moisture-Responsive Wrinkling Dynamic Footwear," a pedagogical design research initiative, demonstrating how it integrates formative design methods based on composite materials, computational strategies, and emerging manufacturing technologies.

Keywords: Biomimicry; Bio-design; Material ecology

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1. Introduction

Over the past centuries, the complex relationship between biology and technology has shaped our view of nature. The form of living organisms is shaped by a complex process known as growth, which involves the direct action of molecular forces as well as other slower processes, such as chemical reactions and osmosis. These forces introduce material into the organism and distribute it within [1]. Just like the processes in nature, human creations also originate from the physical forces of nature [2]. Scottish naturalist and mathematician D'Arcy Thompson, in his 1917 work "On Growth and Form," first presented biology as an example for solving engineering problems. With the rapid advancement of digital and robotic manufacturing technologies in the last decade, rapid prototyping techniques have made the production of complex parts possible. This has given rise to a new body of knowledge that is rapidly evolving in design practice and has led to a new, alternative design method, namely generative design [3].

2. Nature as a technological paradigm - material-driven dynamic design

The rise of generative design represents a significant paradigm shift in the field of design [4]. Historically, the design realm has been constrained by efficiency-centric principles, originating from the era of modernism and driven by mass production. This led to a systematic separation between form, structure, and material, causing incompatibility between design, simulation, and manufacturing [5]. In contrast, generative design, drawing on nature as a technological paradigm, crosses these boundaries. Utilizing digital technologies, it is revealed that the complexity of form within the material composition fosters an integrated understanding of form, material, structure, and environment as a whole, thus achieving a seamless transition from design to manufacturing. Under this new technological paradigm, materials are no longer just minor elements of design form but are transformed into key drivers of design innovation. This introduced a new formative design strategy centered on exploring and harnessing the inherent characteristics and potential of the materials themselves [6].

Meanwhile, this strategy also draws inspiration from the complex forms and evolutionary processes of biological organisms, emphasizing the continuous growth and change inherent in biology. It recognizes that the complex forms and systems of living organisms are the result of a long evolutionary process and that life itself is in a constant state of growth and development [7]. Growth is a complex natural process; as in the material systems of nature, the structural design of an organism is closely related to its evolutionary adaptability [8]. This adaptability is a response to various environmental pressures encountered during development. Although evolution is typically a long-term process, many adaptive phenomena in biology occur over shorter timescales [9]. These phenomena often take place at the individual level rather than across the entire species, making these adaptive changes more observable and easier to study.

This noticeable biological adaptability is exhibited by dynamic biomechanical systems driven by the hierarchical structure of biological materials [10]. The density of fundamental biological materials is usually much lower than that of traditional engineering materials, and their strength comes from a special arrangement of geometric combinations, that is, the heterogeneity of the materials. An example is anisotropic fiber composite materials, which compared to the isotropic rigid materials common in traditional industry, can match their stiffness and strength to withstand the directional force and magnitude of load, thus enabling movement and growth under pressure. During growth, organisms selectively deposit new materials in required areas according to the loads they bear. For example, in bones, material is moved from low-stress areas and redeposited into high-stress areas [11]; in trees, wood with special fiber orientations and porous structures would continuously produce growth rings [12]. These characteristics provide a fundamental framework for biological design, focusing on load-bearing fiber composite materials [13]. Such biomechanical systems, utilizing pre-set tension and variations in expansion and pressure within geometric structures, produce a variety of dynamic behaviors. This dynamic behavior highlights the unique functional and structural aspects of biological materials, especially in terms of adaptability in facing various mechanical challenges.

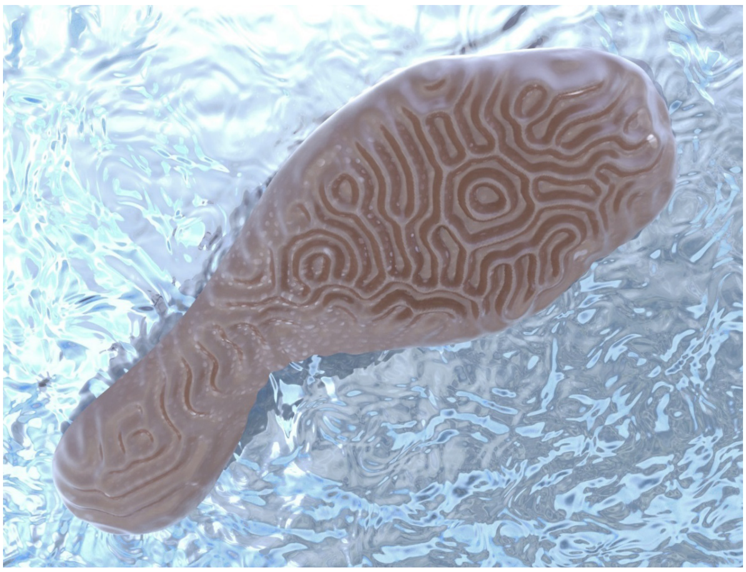

Figure 1. "Moisture-Responsive Wrinkling Dynamic Footwear" project. Synthetic materials were used for the prototype. The procedure was supervised by Shuai Feng, and the photo was taken by Zixiong Wei.

3. “Moisture-Responsive Wrinkling Dynamic Footwear” project

The biodynamic framework based on fiber composite materials has advanced our understanding of dynamic material systems and their adaptability processes. For example, the phenomenon of hygroscopic wrinkling is common in both natural and synthetic materials. In the natural environment, human fingertips form wrinkles after prolonged water immersion and return to smoothness when dry; similarly, facial skin may show fine lines in dry conditions, which diminish with hydration. This structural and functional response of the skin that changes in humidity, known as “Moisture-Responsive Wrinkle Dynamics,” has inspired the concept of a new type of dynamic footwear [14]. This design focuses on composite fiber materials that create footwear that changes sole texture with the humidity of the surrounding environment. This dynamic design is reversible by adjusting the friction of the footwear through dynamic wrinkling. An in-depth study of the characteristics of anisotropic fiber materials and their dynamic wrinkle change, reversible adjustment, and stability enables the footwear to sense and respond to changes in environmental humidity, thus dynamically adjusting its structure and function as shown in **Figure 1** [15,16].

4. Form generation from a material perspective

During the footwear design process, a range of computational techniques, such as finite element analysis, are used to achieve continuous iteration and optimization of the design form. This approach considers not only the static form of the design but also its dynamic wrinkling changes over time, as well as the interaction of the design with external forces, in a process known as ecological intervention. Using this method, the material system is seen as a collaborative outcome formed based on balancing various factors and following different design principles. Here, ecological intervention becomes a distinctive pattern, closely related to the intervention of material physical properties.

In this case, moisture serves as an economical and efficient stimulus to activate the dynamic properties of the fiber material surface. We propose an innovative wrinkle system composed of anisotropic fiber composite materials. This system includes a series of dual-layer structures sensitive to humidity. The layers are made of a hard and hydrophilic polyvinyl alcohol film closely combined with a soft and hydrophobic polydimethylsiloxane film that mimics the wrinkling characteristics similar to the stratum corneum of the skin. When exposed to water, the hard hydrophilic polyvinyl alcohol layer undergoes horizontal wrinkling due to water absorption, while the soft hydrophobic polydimethylsiloxane layer experiences wrinkle deformation under the horizontal compressive force from the hydrophilic layer [14].

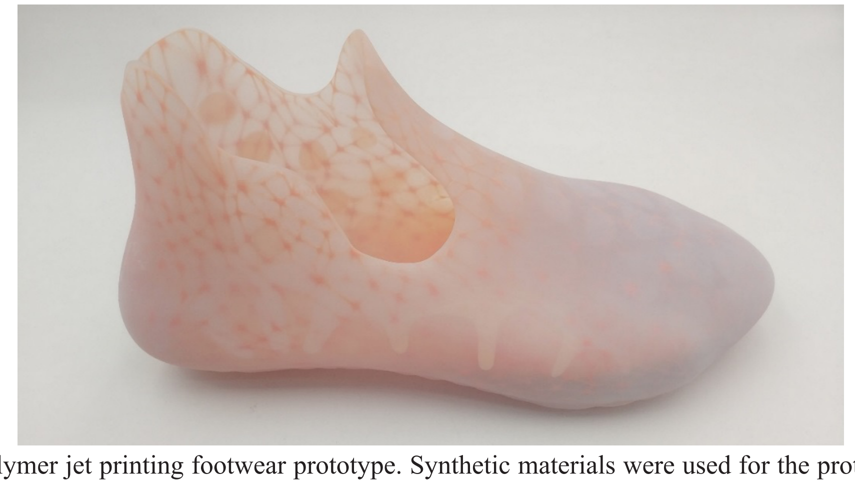

Figure 2. PolyJet polymer jet printing footwear prototype. Synthetic materials were used for the prototype. The procedure was supervised by Shuai Feng, and the photo was taken by Zixiong Wei.

5. PolyJet polymer jet printing prototype

In the field of biology, the application of materials achieves extremely high efficiency and precision, with the process of form generation occurring naturally. The generation of such forms is driven by a pursuit of high performance and resource conservation, as shown in the strategic deployment of anisotropic materials. Such an approach ensures that organisms can achieve optimal strength in function and structure while minimizing material use. In contrast, in traditional engineering, the application of materials is often more wasteful and imprecise, and the process of form generation is more rigid and pre-determined.

The modern computational design environment offers significant potential for transforming traditional engineering methods. The essence of this transformation lies in integrating complex geometric shapes with cutting-edge composite material manufacturing technologies, particularly additive manufacturing technologies like 3D printing. The advancements in these technologies provide designers with an innovative platform, allowing them to consider both the aesthetics of form and the functionality of materials simultaneously in the design process, resulting in the creation of products that are both visually appealing and highly efficient. An exemplary application of this approach is the "Moisture-Responsive Dynamic Footwear" project, which utilizes PolyJet polymer jetting printing technology to create an integrated footwear prototype. This multi-layer polymer jetting technology integrates various biocompatible materials, successfully achieving the project's goals of having diverse and organic characteristics. Utilizing this technology, shoe prototypes can achieve smooth transitions in terms of stiffness, transparency, and color while also being appropriately adjusted according to the designed geometric shape, structure, and chemical properties, as shown in **Figures 2** and **3**.

Figure 3. PolyJet polymer jet printing shoe prototype. Synthetic materials were used for the prototype. The procedure was supervised by Shuai Feng, and the photo was taken by Zixiong Wei.

6. Conclusion

Nature, as a paradigm for technological innovation, is manifested not only in propelling the advancement of manufacturing technologies but also in promoting the process of sustainable form creation, known as morphogenesis within the field of material science. Is it possible to replicate the artificial design of the natural process described by D'Arcy Thompson? If this goal is deemed feasible, then emerging manufacturing technologies, form-creation methods based on composite materials, computational techniques, and innovative projects like the integrated production of shoe prototypes could all become the key drivers for achieving this new form of bio-design.

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