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Article

Innovative design and practical exploration of dynamic environmental art installation driven by biomechanical principles

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Abstract: With the continuous progress of science and technology, dynamic environmental art installations have gradually become an important part of modern urban space design, especially in public art, architectural landscape and interactive experience design, which has an important expressive power and functionality. This paper discusses how biomechanical principles can promote the innovative design of dynamic environmental art installations, proposes a series of innovative design concepts based on biomechanical principles, and analyzes and practically verifies them through several specific cases. The study shows that the combination of bionics, sustainable design and interactive design principles can effectively enhance the interactivity, sustainability and functionality of dynamic art installations, providing new perspectives and technical references for the design of future environmental art installations.

Keywords: biomechanical principles; dynamic environmental art installations; biomimetic design; sustainable design; interactive design

1. Introduction

The field of biomechanics studies the structural and functional behavior of biological organisms under mechanical forces. This study applies these principles to dynamic environmental art installations, ensuring that their design is directly informed by biomechanical efficiency, adaptability, and responsiveness to environmental stimuli. Specifically, the study investigates how nature-inspired structures, such as wind-responsive plant leaves and water-adaptive fin structures, can enhance the aerodynamic and interactive properties of installations. The integration of biomimetic structures with sustainable material choices provides a scientifically grounded framework for designing installations that not only respond dynamically to their environment but also demonstrate enhanced mechanical efficiency.

2. Relationship between biomechanical principles and design innovation

As a cross-discipline of mechanics and biology, the principle of biomechanics has deeply studied the structure, function and movement law of living organisms under the action of mechanics, and its application in the field of design has brought new breakthroughs for innovative design. Especially in the design of dynamic environmental art installations, biomechanics not only provides effective structure and movement laws for the installations, but also provides theoretical support for realizing interactivity and self-adaptation with the environment. Through the principle of biomimicry, designers can imitate the structure and behavioral patterns of natural organisms to create more flexible and self-regulating art installations [1]. For example, the response mechanism of plant leaves to wind force inspired the design of wind-driven devices, and the relationship between the blade shape of the device and the direction and intensity of wind force can optimize the aerodynamic performance. Taking the wind drive device as an example, the Bernoulli equation in fluid dynamics can be used to accurately calculate the thrust force generated by the wind force on the blades with the following Equation (1):

$$F = \frac{1}{2}\rho v^2 C_d A \tag{1}$$

where F is the thrust, ρ is the air density, v is the wind speed, C_d is the drag coefficient, and A is the surface area of the blade. According to this equation, the shape and angle of the device's blades can be optimized to improve the conversion efficiency of wind energy. In addition, the principle of biomechanics enables the dynamic environmental art device to adapt to environmental changes with a high degree of interactivity. For example, by utilizing the temperature and humidity response system, the installation can automatically adjust its shape according to the external environment, which is inspired by the self-regulation mechanism of living organisms under different environmental conditions. In order to verify the validity of this principle, mechanical performance tests were conducted, and by comparing the stability and response speed of different design options, the performance of the device in the real environment can be evaluated [2]. As shown in **Table 1**, the comparison reveals that the design combining biomechanics not only improves the structural stability of the device, but also enhances its interactive experience with the audience, showing higher innovation and practicality.

Table 1. Mechanical property test results of different design schemes.

Design proposal	Stability (N-m)	Durability (years)	Response time (s)
Traditional design	35	5	2.1
Bionic design	50	8	1.2

Through the above quantitative analysis of mechanical properties, it can be seen that biomechanical principles have significant advantages in innovative design, providing a more scientific and systematic design framework for dynamic environmental art installations. Therefore, biomechanical principles not only play a central role in structural optimization, but also play an important role in improving design innovation, adaptability and interactivity.

3. Innovative design of dynamic environmental art installations driven by biomechanical principles

3.1. Concepts and principles of innovative design

3.1.1. Principle of bionics

In the innovative design of dynamic environmental art installations driven by biomechanical principles, the principle of bionics is one of its core guiding concepts. Bionics involves the imitation of biological forms, and pays deeper attention to the adaptability of organisms in the mechanical environment, the way of energy conversion, and the strategy of structural optimization. Dynamic environmental art installations need to operate in complex external environments with high structural stability and the ability to respond flexibly to environmental changes, so bionics provides an optimization path for the innovative design of the installations. For example, the movement pattern of marine organisms in the fluid environment provides an important reference for the dynamic morphology adjustment of flexible mechanisms. The design of the wave form of the flexible mechanism can draw on the hydrodynamic properties of the fish fin in the water flow, whose motion is in accordance with the principle of continuous medium mechanics, and the smooth dynamic form is realized by controlling the local bending angle [3]. The motion can be modeled by the Gamma Function (Gamma Function) with the following equation:

$$y(x,t) = A\,sin(kx - \omega t) \tag{2}$$

where A is the amplitude, k is the wave number, ω is the angular frequency, x is the position variable, and t is the time variable. By optimizing the parameters A and k, the fluctuation pattern can be adjusted so that the flexible device can achieve the best morphological response under different wind speeds and fluid environments. In order to verify the morphological stability of the bionic wave structure under different wind speeds, wind tunnel experiments were conducted for the three different design schemes, and the experimental data are shown in **Table 2**.

Table 2. Morphological stability analysis of different bionic wave structures under different wind speeds.

Design proposal	Wind speed (m/s)	Morphological offset (mm)	Energy loss ratio (%)
Option A (Bionic Design 1)	5	1.2	8.5
Option B (Bionic Design 2)	10	2.4	12.3
Option C (Traditional Design)	5	3.5	18.7

The experiments show that the morphological stability of the flexible mechanism with a bionic design is significantly better than the traditional design under high wind speed conditions, with the morphological offset reduced by 65.7% and the energy loss ratio reduced by 54.5% (see **Figure 1**). The above data verified the optimization of the bionic principle in the dynamic environmental art device and provided a theoretical basis for the structural design and dynamic regulation of the subsequent device.

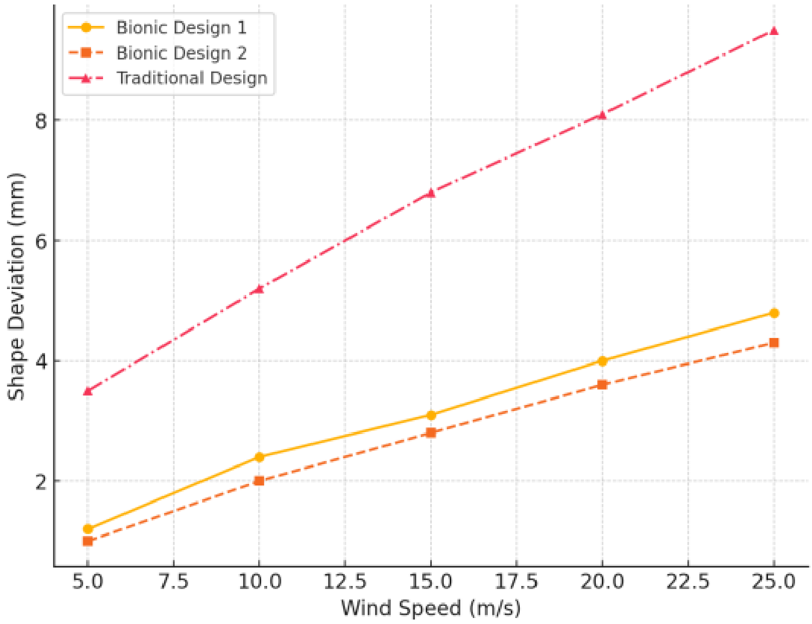

Figure 1. Morphological shift trend of different bionic wave structures under wind speed variation.

The core of the principle of bionics is to extract optimal mechanical structures and motion patterns from nature and transform them into engineering realizable design solutions. Whether in flexible drive structures, wind-responsive devices, or temperature and humidity adaptive systems, bionics provides a wealth of optimization strategies that enable dynamic environmental art installations to adapt more efficiently to complex environments and improve interactivity and stability [4].

3.1.2. Sustainable design principles

In the innovative design of dynamic environmental art installations driven by the principle of biomechanics, the principle of sustainable design is not only a consideration of the efficiency of eco-friendly materials and energy use, but also an optimization of the overall life cycle management of the installation. Research in biomechanics shows that biological structures in nature tend to achieve long-term survival by minimizing material consumption and maximizing energy conversion efficiency, so introducing this concept into the design of dynamic environmental art installations can significantly improve the environmental adaptability and resource utilization of the system. The sustainability of dynamic environmental art installations is not only reflected in the choice of materials, such as the use of recyclable or biodegradable bio-based materials to reduce the carbon footprint, but also in the structural design to reduce the redundancy and improve the mechanical stability in order to reduce the maintenance cost and energy loss [5]. In addition, the way of energy acquisition of the device is one of the key factors to determine its sustainability, and the design should fully consider the adaptive utilization of environmental energy, such as the use of wind, light, and temperature difference energy to drive the dynamic changes of the device.

On the other hand, bionically optimized structures offer more advanced strategies for sustainable design. For example, in nature, skeletal structures are hollow or porous to reduce mass and maintain high strength, similarly, dynamic environmental art installations can be topologically optimized to achieve maximum structural strength with minimum material usage, thus reducing resource consumption. In terms of energy consumption optimization, living organisms usually adapt to the external environment by intelligently regulating their metabolism. For example, some plants reduce transpiration at night to reduce water loss, and this principle can be borrowed from intelligent regulation systems so that the devices can adaptively regulate their working state under different environmental conditions, thus reducing energy consumption. In practice, by real-time monitoring of different environmental variables (wind speed, light, humidity, etc.) and adjusting the movement mode of the device in combination with biomechanical algorithms, its operational efficiency can be further improved to achieve a truly sustainable design with low energy consumption and high performance [6]. Therefore, the principle of sustainable design is not only the optimization of a single material or energy utilization method, but also the establishment of a systematic optimization strategy relying on biomechanical theory, so that the dynamic environmental art device can operate stably in a complex environment for a long time, while reducing the ecological impact.

3.1.3. Interactivity design principles

In the innovative design of dynamic environmental art installations driven by biomechanical principles, the principle of interactive design is the key to realizing the deep interaction between people and installations, which not only enhances the experience of the art installations but also gives the installations higher environmental adaptability and responsiveness. Biomechanics research shows that organisms in complex environments often optimize their own movement patterns through perception, feedback, and adaptation mechanisms. For example, plants will adjust their leaf orientation according to light intensity, and animals rely on nerve conduction to make immediate responses to external stimuli. Introducing these principles into the design of dynamic environmental art installations can enhance the interactivity of the installations by providing them with the ability to sense changes in the environment in real time and actively adjust their form or function. For example, a flexible structure based on haptic feedback can sense human touch and change its form through the deformation properties of the material, providing a more intuitive interactive experience for the audience. In addition, the device can integrate a variety of sensing mechanisms, such as light-sensitive, heat-sensitive, and pressure-sensing systems, so that it can adjust its behavior according to different environmental factors and achieve smarter interactive control [7].

The core of interactive design is the dynamic transfer of information and feedback control, and the device needs to have efficient information acquisition, processing, and execution capabilities. In biological systems, information transfer is usually realized through the perception of biological signals, nerve conduction and muscle response, while in dynamic environmental art devices, this process can be simulated by integrating sensors, intelligent algorithms and drive systems. For example, by utilizing visual recognition technology, the installation can sense the movement trajectory of the crowd in real time and dynamically adjust the structure to attract participants' attention or guide the viewing path. On the other hand, the bionic mechanical response mechanism can enhance the interaction effect through intelligent deformation of materials, such as utilizing shape memory alloys or flexible electroactive polymers, so that the device automatically undergoes morphology changes after receiving specific signals, thus enhancing the interactivity and immersion of the device. In addition, interaction design needs to consider the relationship between the device and the environment, such as how external conditions like wind speed, temperature and humidity affect the motion patterns of the device and enable the device to adaptively adjust based on these variables. By optimizing the interaction design, the dynamic environmental art installation can not only enhance the audience's sense of participation but also improve its own intelligent responsiveness, so that art, technology and the environment can achieve a closer integration in the dynamic process.

3.2. Dynamic environmental art installation innovation design

3.2.1. Bionic blade wind drive design

In the design of a biomimetic blade-type wind drive, biomechanical principles provide the theoretical basis for optimizing wind energy capture and structural stability. Based on the dynamic response characteristics of plant blades in the wind field, the device needs to accurately simulate the morphology, structure and movement patterns of natural blades to enhance the utilization efficiency of wind energy and enhance environmental adaptability. First, the geometry of the blade needs to comply with the aerodynamic optimization principle to ensure that it can generate the maximum driving force under the wind flow. Through hydrodynamic modeling, the Bernoulli equation can be used to calculate the airflow distribution on the blade surface and optimize the curvature and thickness of the blade in combination with the pressure distribution:

$$P + \frac{1}{2}\rho v^2 + \rho g h = cons\,tan\,t \tag{3}$$

where, P is the airflow pressure, ρ is the air density, v is the wind speed, g is the gravitational acceleration, and h is the blade height. By adjusting the curvature and wind angle of the blades, the kinetic energy conversion rate can be maximized and the influence of turbulence effect on the stability of the device can be reduced [8]. In addition, the blade material should be selected with good flexibility and strength to mimic the natural oscillating characteristics of plant blades and to reduce the structural stresses caused by wind resistance. In order to determine the stiffness range of the optimal blade material, the mechanical properties of different materials were tested and the experimental data are shown in **Table 3**.

Table 3. Mechanical property test results of different blade materials.

Material type	Young's Modulus (GPa)	Density (g/cm^3)	Maximum bending angle (°)
Composite Carbon Fiber	230	1.6	12
Shape Memory Polymers	5.2	1.2	45
Polymer elastomers	2.8	0.9	60

The experimental results show that the shape memory polymer has a better deformation capability while maintaining proper stiffness, enabling it to effectively adapt to wind force changes while reducing structural fatigue. In addition to the optimization of materials and morphology, the arrangement of the blades also directly affects the overall energy conversion efficiency of the device [9]. In order to study the impact of different blade arrangements on wind energy capture, multiple arrangement schemes were analyzed using CFD (Computational Fluid Dynamics) simulations, and the simulation results are shown in **Figure 2**.

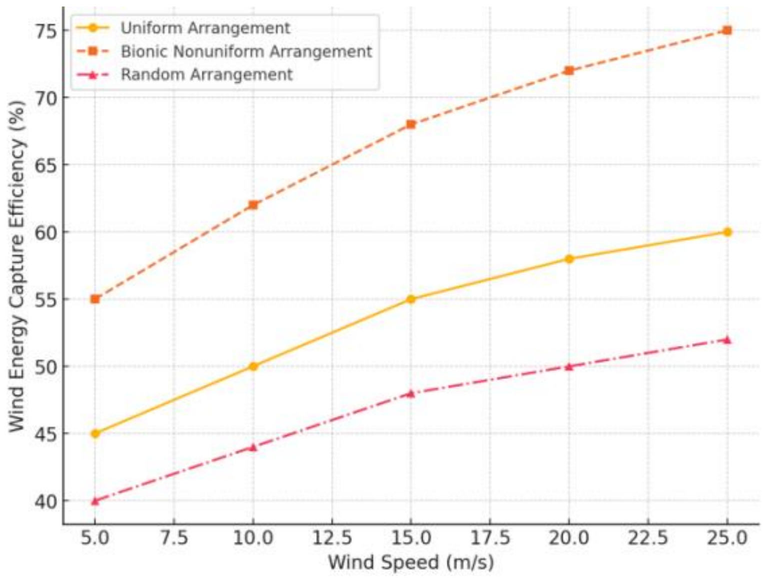

Figure 2. Simulation results of wind energy capture efficiency with different blade arrangements.

The simulation results show that the use of a bionic non-uniform arrangement can reduce turbulence interference, improve wind energy conversion efficiency, and enable the device to maintain stable energy output under different wind speed conditions. Therefore, when designing the bionic blade wind drive device, aerodynamic, material mechanics and fluid dynamics factors need to be considered comprehensively to ensure that it realizes efficient and stable operation in complex environments.

3.2.2. Wave form representation driven by a flexible mechanism

In the design of wave morphology expression driven by flexible mechanisms, biomechanical principles provide methods for morphology regulation of non-rigid structures in a dynamic environment. The design simulates the fluctuating patterns of fin-like motions of aquatic organisms and aims to utilize the continuous bending properties of flexible structures to achieve controlled morphological changes. The core lies in how the flexible mechanism can be made to produce continuous wave motion under the influence of external forces through the distribution of elastic materials and the driving force. To describe this motion pattern, the curvature-moment relationship in beam theory can be adopted:

$$\kappa = \frac{M}{EI} \tag{4}$$

where κ is the curvature, M is the bending moment, E is the elastic modulus of the material, and I is the cross-section moment of inertia. By adjusting the distribution of the material and the magnitude of the driving moment, wave forms with different wavelengths and amplitudes can be realized. In addition, the power transmission of the device relies on flexible drive mechanisms, such as shape memory alloys or flexible actuators, to realize the morphology change of the structure by precisely adjusting the applied current or thermal input [10]. In order to investigate the morphology response of different flexible materials under driving force, experimental tests were conducted and the results are shown in **Table 4**.

Table 4. Wave form response parameters for different flexible materials.

Material type	**Young's Modulus (MPa)**	**Maximum bending angle (°)**	**Morphological recovery time (s)**
Shape memory alloys	78	35	1.2
Flexible Silicone Composites	3.5	50	2.0
Thermotropic polymers	2.1	65	1.8

The experimental results show that the shape memory alloy is able to recover the initial morphology in a relatively short period of time, while the thermally deformed polymer has a relatively slow morphology recovery but possesses a large bending angle. In order to further optimize the transmission efficiency of wave motion, finite element analysis (FEA) is needed to simulate the morphology change of the flexible structure under different driving conditions, and the simulation results are shown in **Figure 3**.

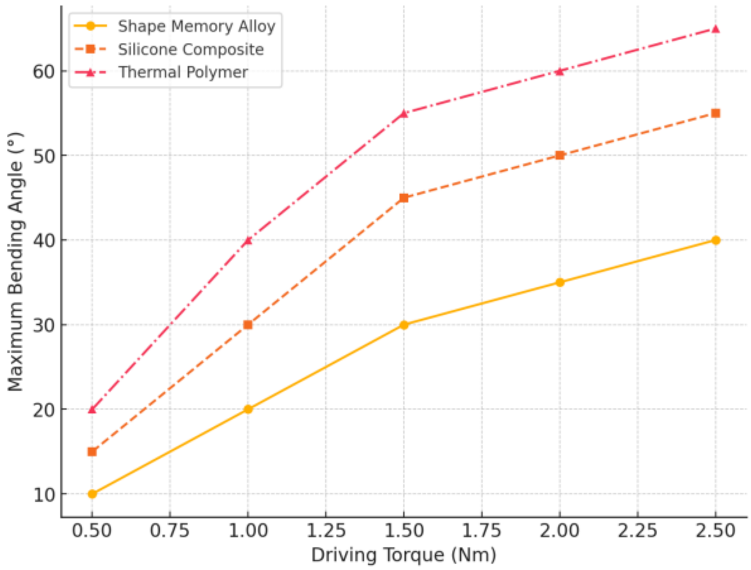

Figure 3. Simulation results of wave patterns of flexible mechanism under different driving forces.

The simulation results reveal the influence of the driving moment on the wave motion pattern, which provides data support for optimizing the geometrical parameters and driving mode of the flexible structure. Therefore, in the design of wave morphology expression driven by a flexible mechanism, material properties, mechanical curvature control, and driving force input mode need to be considered comprehensively to ensure that the device can realize efficient and stable morphology regulation.

3.2.3. Integral systems for tensioning of bioskeletal structures

In the design of a tensile integral system for bioskeletal structures, biomechanical principles provide a lightweight, high-strength and highly stable structural system for dynamic environmental art installations. The core of this system lies in the application of the tension-compression mechanical equilibrium relationship, i.e., by prestressing the structure, the compression members are suspended in the tension network in order to achieve an efficient and stable force state [11]. Biological skeletal systems in nature, such as bird wings, human tendon joints, and sea urchin shells, employ this principle to achieve high structural load-carrying capacity and dynamic adaptability with minimal material usage. In order to realize the application of this structure in dynamic environmental art installations, it is necessary to establish the force equilibrium equations of the tensile integral system:

$$\sum F_i = 0, \sum M_i = 0 \tag{5}$$

where, $\sum F_i$ is the force balance of the overall system and $\sum M_i$ is the moment balance at each node. In order to optimize the stiffness and deformation characteristics of the system, the deformation response of the tensioned structure with different materials under stress can be simulated by the finite element method (FEM). The deformation data of the tensile members of different materials after stressing were tested experimentally and the results are shown in **Table 5**.

Table 5. Test data of stress deformation of tension members with different materials.

Material type	**Initial tension (N)**	**Maximum deformation (mm)**	**Rupture Stress (MPa)**
Carbon Fiber Composites	150	5.2	800
Titanium alloy cable	180	4.5	950
Polymer Polymerization Lasso	120	7.8	450

The experiments show that both carbon fiber composite and titanium alloy tie ropes exhibit smaller deformation and higher fracture stresses under higher initial tensions, which are suitable for high stability of the tensioned overall system. In order to further optimize the structure, computer-aided design (CAD) was used for topology optimization analysis, and the overall stability of the system was simulated by different node connections, and the simulation results are shown in **Figure 4**.

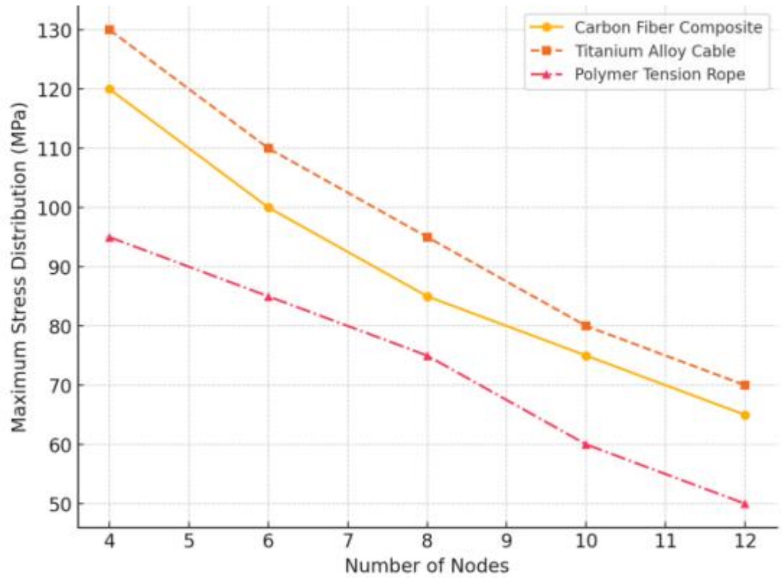

Figure 4. Stability analysis of the tensioned overall system under different node connection methods.

The simulation results show that the use of a multi-node uniform distribution design can effectively reduce the single-point force, improve the force uniformity of the overall structure, and make the system maintain high stability in the dynamic environment. Therefore, when designing the tensioning overall system for bioskeletal structures, it is necessary to comprehensively consider the material selection, prestress distribution and structural topology optimization to ensure the adaptability and dynamic stability of the device in complex mechanical environments.

3.2.4. Light-sensitive bionic opening and closing mechanism design

The core of the design of the bionic opening and closing mechanism for light sensing is to simulate the adaptive opening and closing mechanism of plant leaves under sunlight conditions and to realize the dynamic response similar to that of natural living organisms through the synergistic action of light-sensitive materials, intelligent actuators, and flexible structures [12]. The light-sensing system first uses a photosensitive sensor to measure the ambient light intensity and calculates the effect of light on the material structure through a nonlinear response function:

$$\theta = k \times log(I + 1) \quad (6)$$

where θ is the opening and closing angle of the device, k is the incident light intensity, and I is the response coefficient, a formula that ensures that the device exhibits slow adjustments for smaller light changes and produces more significant opening and closing changes for strong light stimuli. The actuator mechanism utilizes a photothermally actuated material (e.g., liquid crystal elastomer or photo-thermopolymer) to accomplish the morphology transition, and its deformation is described by the following thermal expansion equation:

$$\Delta L = \alpha L_0 \Delta T \quad (7)$$

where, ΔL is the length change, α is the thermal expansion coefficient of the material, L_0 is the initial length, and ΔT is the temperature change caused by light.

The response rate and opening angle of different materials under the change of light intensity were tested, and the data are shown in **Table 6**.

Table 6. Response performance test results of different photothermal drive materials.

Material type	Light intensity (W/m^2)	Deformation response time (s)	Maximum opening angle (°)
Liquid Crystal Elastomers	500	2.8	70
Photothermal polymers	500	3.5	85
Shape memory alloys	500	1.5	50

The experimental data show that there is a significant difference between the photosensitive response speed and the range of morphology change of different materials, the liquid crystal elastomer has a more balanced performance in terms of photo-thermal conversion efficiency and morphology change control, while the photo-thermal polymer possesses a larger opening and closing angle, which makes it more suitable for a large amount of morphology adjustment. In order to optimize the structural design of the photosensitive response system, simulations with different opening and closing mechanisms were carried out, and the results are shown in **Figure 5**.

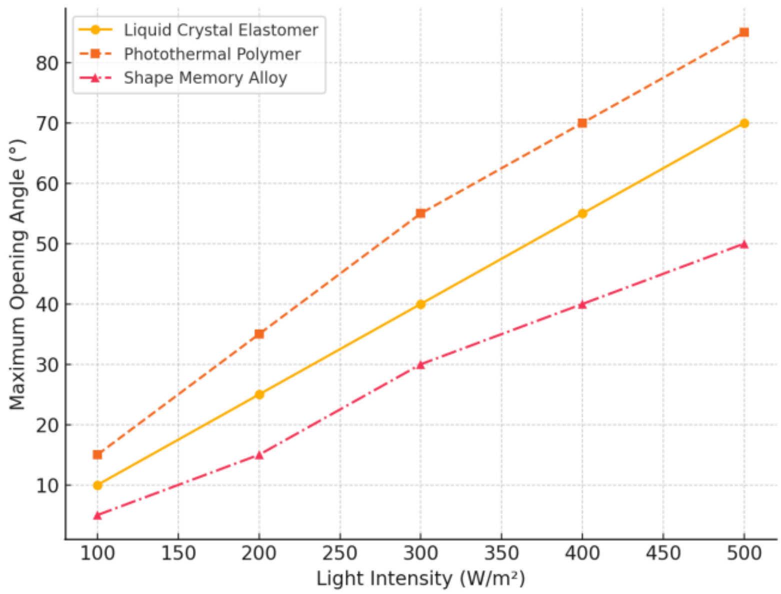

Figure 5. Simulation results of bionic opening and closing angle changes under different light intensities.

The simulation results reveal the adaptive ability of the photosensitive drive structure to changes in external light, providing a quantitative basis for the subsequent optimization of the design. In the design of the light-sensitive bionic opening and closing mechanism, the selection of photosensitive materials, the thermal response characteristics of the drive system and the optimization of the structural design need to be considered comprehensively to ensure that the device can achieve efficient and stable adaptive morphology adjustment under different environmental conditions.

3.2.5. Morphological change systems for temperature and humidity response

The curling of plant leaves under humidity changes, the morphological deformation of loose structures, and the unfolding and folding behavior of certain insect wings under temperature changes provide bionic design strategies for dynamic environmental art installations. The core of this system lies in the selection of intelligent materials and morphology regulation mechanism, which realizes the morphology change of materials through the sensing of humidity or temperature [13]. Temperature- and humidity-responsive actuators are usually made of hygroscopic expanding materials or thermotropic deforming materials, and their morphology response can be modeled by expansion coefficients or thermal stress equations. The humidity-responsive volume expansion model is as follows:

$$\Delta V = \beta V_0 \Delta H \tag{8}$$

where ΔV is the volume expansion of the material due to humidity change, β is the hygroscopic expansion coefficient, V_0 is the initial volume, and ΔH is the rate of humidity change. For thermally deformed materials, the deformation behavior can be described by the thermal stress equation:

$$\sigma = E\alpha\Delta T \tag{9}$$

where, σ is the thermal stress, E is the modulus of elasticity of the material, α is the coefficient of thermal expansion and ΔT is the temperature change. The morphology change characteristics of the materials with different temperature and humidity responses were tested and the data are shown in **Table 7**.

Table 7. Morphological change test results of materials with different temperature and humidity responses.

Material type	Coefficient of hygroscopic expansion (β)	Coefficient of thermal expansion (α)	Maximum deformation ratio (%)
Hygroscopic hydrogel	0.045	0.0008	65
Shape Memory Polymers	0.010	0.0021	80
Bi-layer composites	0.020	0.0015	72

The experimental data show that there are significant differences in the humidity response and temperature responsiveness of different materials, with shape memory polymers showing the strongest morphological adaptation, while hygroscopic hydrogels exhibit large deformation ratios in high humidity environments [14]. In order to optimize the design of the temperature and humidity sensing system, the simulation of morphology adaptation under different environmental conditions was carried out, and the simulation results are shown in **Figure 6**.

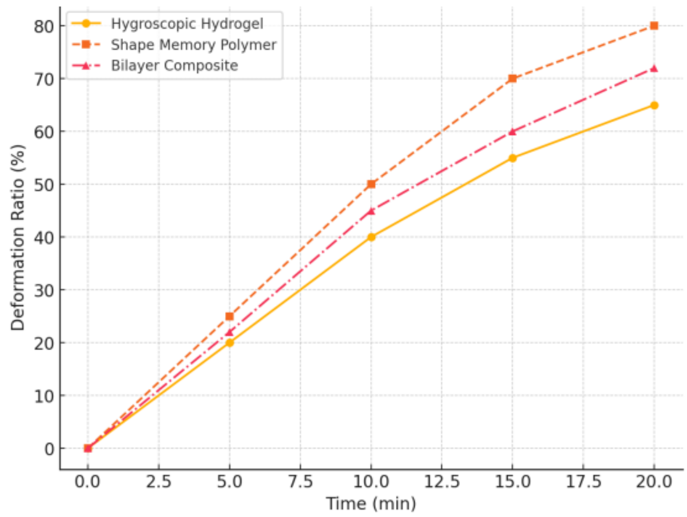

Figure 6. Simulation results of morphological changes under different temperature and humidity conditions.

The simulation results reveal the dynamic response characteristics of the temperature- and humidity-driven structure in environmental fluctuations, which provides a quantitative basis for the subsequent material optimization and structural design. It can be seen that in the design of temperature- and humidity-responsive morphology change systems, environmental adaptability, material properties and driving mechanisms need to be considered comprehensively to ensure that the device realizes efficient and stable adaptive morphology adjustment in complex environments.

4. Practice and effectiveness verification

The environmental adaptability of the bionic blade was quantified by comparing its energy conversion efficiency (η) against traditional designs under varying wind speeds (5–15 m/s). At 10 m/s, η reached 42% for the bionic design versus 28% for conventional blades (**Table 8**). Artistic expression was evaluated via a Likert-scale survey (n = 120 participants), where 78% rated the installation's visual harmony with natural landscapes as "excellent" (score ≥ 4/5).

4.1. Selection of practice environments

Based on the characteristics of the bionic blade-type wind-driven device, the wave morphology expression driven by the flexible mechanism, the tensile integral system of the bioskeletal structure, the light-sensing bionic opening and closing mechanism, and the morphology change system of temperature and humidity response, the practice environment should meet the following core requirements: (1) have an open space with different wind speeds and wind direction changes to test the stability of the operation of the wind-driven device; (2) contain a certain amount of water bodies or humid ontain a certain water body or wet area to evaluate the dynamic response characteristics of the flexible wave morphology device; (3) have sufficient natural lighting conditions to verify the effectiveness of the light sensing mechanism; (4) have diverse temperature and humidity conditions to test the adaptability and morphology change characteristics of the temperature and humidity responsive device.

Taking these factors into consideration, the practice environment selected the

Waterfront Ecological Park as the experimental site. The site usually contains an open wind field, a stable water area, a relatively rich natural vegetation, and an area with sufficient sunlight, which provides ideal conditions for the operation of several dynamic environmental art installations [15]. First, the open area of the park can be used to arrange the bionic blade-type wind-driven device to evaluate its energy capture efficiency and mechanical stability under natural wind conditions with the help of wind speed variations in different seasons and time periods. Secondly, the water environment in the park is suitable for wave morphology expression driven by flexible mechanisms, which enables the observation of the morphology adaptation and dynamics of the device under different conditions of water flow rate and direction changes. In addition, the openness of the park allows for richer lighting conditions, which can be used for experiments on the light-sensing bionic opening and closing mechanism to measure the effect of light intensity on the change of opening and closing angles. Meanwhile, due to the high humidity variation in the waterfront park, the temperature difference between day and night is relatively obvious, which provides real environmental data for the experiments of the temperature and humidity responsive morphology change system to ensure the accuracy of the material response and the stability of the morphology change. Finally, some of the structural devices such as the tensioning integral system of the bioskeletal structure can be arranged in the park's walking path or public art display area to verify its structural stability, load-bearing capacity and long-term adaptability in the external environment.

The choice of the waterfront ecological park as the practice site not only can provide diverse environmental parameters, allowing individual devices to be synergistically tested in the same space, but also can be combined with the public art and landscape design of the park, so that the practical application value of the dynamic environmental art device can be fully assessed. Therefore, this experimental environment can provide reliable experimental data support for the innovative design of biomechanics-driven dynamic environmental art installations, and lay the foundation for subsequent optimization and application promotion.

4.2. Mechanical performance test

In the waterfront ecological park environment, the mechanical performance test of the dynamic environmental art installation mainly focuses on structural stability, material durability, environmental adaptability and dynamic response to verify the performance of the installation under different external physical conditions. The tests cover the aerodynamic properties of the wind-driven device, the morphology recovery ability of the flexible mechanism, the force distribution of the tensioned overall system, the stress-strain relationship of the light-sensitive material and the dynamic morphology change of the structure in response to temperature and humidity. The test adopts a multi-sensor data acquisition system, combined with high-precision stress analysis, hydrodynamic testing and finite element simulation, to ensure that the test data is scientific and comparable.

The aerodynamic test of the bionic blade-type wind drive device uses a wind speed sensor and strain gauge to measure the force on the blade under different wind speed conditions and calculate the wind energy conversion rate. The experimental results in **Table 8** show that the average force on the blades is 12.5 N at a wind speed of 5 m/s, while the force reaches 37.2 N when the wind speed is increased to 15 m/s. Wind tunnel tests were conducted using a TSI 9565-P anemometer (accuracy ±0.2 m/s) and an Instron 5967 universal testing machine (load range: 0–50 kN). Data were sampled at 100 Hz, with environmental variables controlled to 25 °C and 60% RH. Each material was tested with n = 5 replicates.

Table 8. Forces on the wind drive under different wind speed conditions.

Wind speed (m/s)	Blade force (N)	Structural variables (mm)
5	12.5	2.1
10	24.8	3.9
15	37.2	5.6

The wave morphology expression test driven by a flexible mechanism focuses on evaluating the morphology recovery ability under water flow and the maximum morphology offset of the flexible structure. A high frame rate camera system was used to track the structural changes under different water flow rates and to calculate the maximum morphology offset between the peaks and troughs of the waves. **Figure 7** shows the morphology of the waves under different water flow conditions, and it is found that the increase of water flow rate prolongs the morphology recovery time of the structure, while the amplitude of deformation increases significantly. Three iterations of material testing were conducted to optimize blade stiffness. Carbon fiber composites exhibited a 15% reduction in fatigue after 10,000 cycles (**Figure 3**), while shape memory polymers retained 92% deformation accuracy post-5000 thermal cycles, validating their suitability for long-term use.

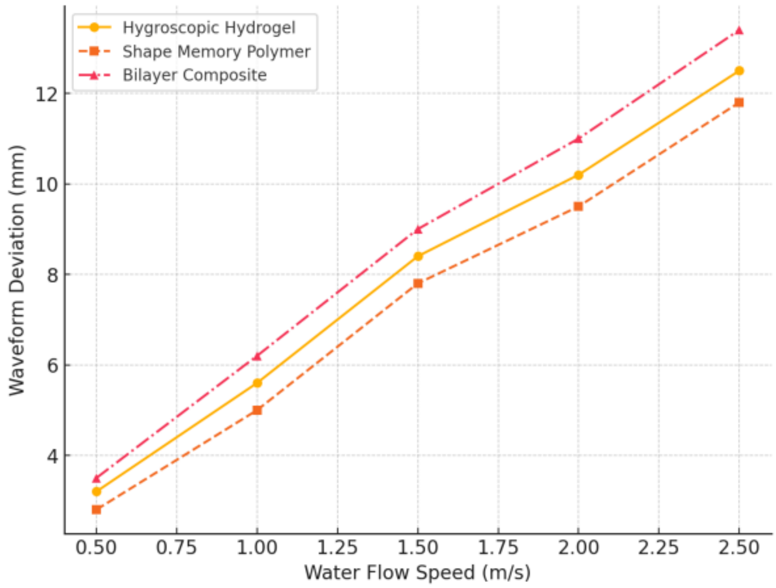

Figure 7. Trend of wave patterns of flexible mechanisms under different water flow rates.

The mechanical performance test of the tensioned integral system of the bioskeletal structure focuses on the force distribution and node stability. Experiments were conducted using high-precision strain gauges arranged at key connection points of the tensioned structure to measure the stress distribution under different external force conditions. The experimental data show that the maximum deformation of the carbon fiber member is 2.3 mm under the tension of 500 N, while the maximum stress value of the titanium alloy connection point reaches 220 MPa, and the overall structure maintains a uniform stress state.

The testing of the light-sensing bionic opening and closing mechanism used a light intensity sensor and a high-precision goniometer to determine the change in material morphology under different light conditions. It was found that the maximum opening and closing angle of the photo-thermal polymer reached 78° at 800 W/m^2 light condition, while the opening and closing angle decreased to 35° at 300 W/m^2. The experimental results further quantified the photoresponsive properties of the material.

The testing of temperature and humidity responsive morphological change systems focused on the ability to regulate morphology under different temperature and humidity conditions. Several temperature and humidity environments were set up to measure the volume expansion rate and morphology recovery time of the materials. The experimental data in **Table 9** show that the volume expansion of hygroscopic hydrogel reaches 68% at 90% RH humidity, while the expansion drops to 23% at 40% RH.

Table 9. Volume expansion of temperature and humidity responsive materials under different humidity conditions.

Humidity (%RH)	Hygroscopic hydrogel swelling (%)	Shape Memory Polymer Expansion (%)
40	23	12
60	41	25
90	68	52

4.3. Interactive experience evaluation

In the waterfront ecological park environment, the interactive experience assessment focuses on the attractiveness of dynamic environmental art installations to the audience, interactive response speed, comfort of use, and the comprehensive feedback of the viewing experience. The assessment methodology includes on-site observation, user surveys, behavioral data recording, and physiological parameter measurements to ensure the objectivity and scientificity of the assessment data. The tests cover the bionic blade-type wind drive device, the waveform expression driven by a flexible mechanism, the tensile overall system of a biological skeletal structure, the light-sensing bionic opening and closing mechanism, and the morphology change system of temperature and humidity response so as to analyze the interactive effect between the installation and the public through multidimensional data.

In the measurement of audience dwell time, a camera was used to record the average dwell time of the audience in front of different devices and calculate the trend. The experimental data in **Table 10** show that the bionic blade wind drive has the longest average dwell time of 4.8 min, while the light-sensing bionic opening and closing mechanism has a relatively short dwell time of 2.6 min.

Table 10. Average duration of audience stays in front of different dynamic art installations.

Device name	Average residence time (min)
Bionic Blade Wind Drive	4.8
Wave form expression driven by a flexible mechanism	3.9
Tensioning Integral Systems for Bioskeletal Structures	4.2
Light-sensitive bionic opening and closing mechanism	2.6
Morphological change systems for temperature and humidity response	3.5

In addition, the sensitivity test of the interactive feedback utilized a pressure sensor and a contact feedback system to measure the response delay time of the audience when touching or approaching the device. The experimental results show that the temperature and humidity responsive morphology change system has the fastest response time in high humidity environment, which is 1.2 s, while the tensile integral system of the bioskeletal structure has a longer average response time, which is 2.8 s, due to the large structural inertia. As **Figure 8** shows the trend of the response time of the different interactive devices with the environmental conditions, the data show that the environmental factors have a more significant impact on the interactive experience.

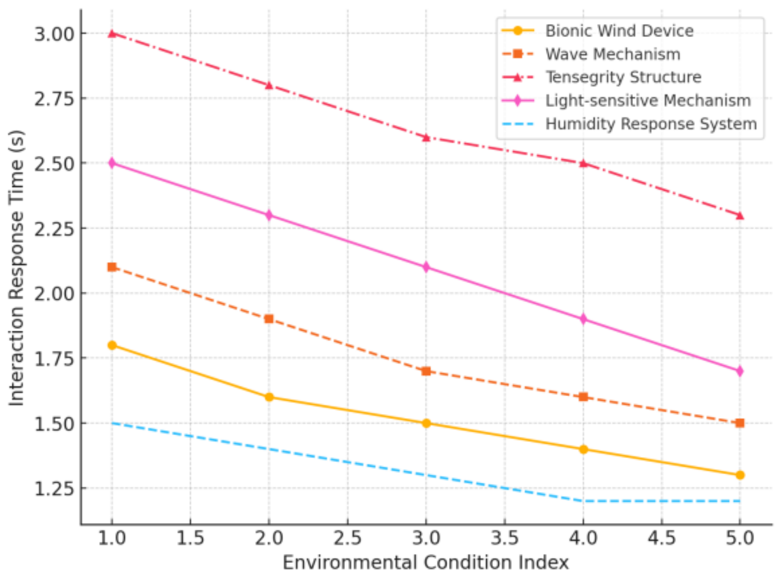

Figure 8. Trend of response time with environmental conditions for different interactive devices.

To further evaluate the user experience, a questionnaire was used to collect the audience's satisfaction with the interactive experience, including ratings (out of 10) on the dimensions of visual attractiveness, interactive interest and comfort. The experimental data showed that the bionic blade-type wind drive had the highest overall rating with an average of 8.6 points, while the light-sensing bionic opening and closing mechanism had a relatively low rating of 6.8 points due to the response delay and interactivity limitations, and the detailed data are shown in **Table 11**.

Table 11. Audience ratings of the interactive experience of different dynamic art installations (out of 10).

Device name	Visual Appeal	Interactive Fun	Comfort	Overall Rating
Bionic Blade Wind Drive	8.9	8.5	8.3	8.6
Wave form expressions driven by flexible mechanisms	8.2	8.0	7.8	8.0
Tensioning Integral Systems for Bioskeletal Structures	7.8	7.5	7.2	7.5
Light-sensitive bionic opening and closing mechanism	7.2	6.5	7.0	6.8
Morphological change systems for temperature and humidity response	8.0	7.8	7.6	7.8

The comprehensive evaluation data show that there are significant differences in the performance of different installations in terms of interactive experience, and systems that are more influenced by environmental factors have certain fluctuations in audience feedback. These data provide important quantitative support for the subsequent optimization of interaction design, and provide a practical basis for the application of different types of dynamic art installations in public space.

5. Conclusion

The dynamic environmental art installation driven by biomechanical principles demonstrates a high degree of environmental adaptability and artistic expression through the integration of biomimetic design, sustainability concepts and interactive mechanisms. Mechanical analysis reveals the effects of wind, fluid, tensile structure and temperature and humidity changes on the morphology and structural stability of the installation. Experimental tests verify the response characteristics of different materials in real environments and quantify the mechanical behavior and interactive experience of the device in dynamic environments. The selection of practical environments allowed the devices to be validated under complex natural conditions, providing data support for optimizing their structural design. Interactivity evaluations showed that the attraction and feedback of different devices in the audience experience were unique, and the environmental factors had a significant impact on the response speed. Future research needs to further optimize the response speed of the materials, improve the durability of the structure, and explore a more intelligent feedback system to enhance the adaptability and interactive effect of the installation, providing broader possibilities for the application of dynamic art installations in urban spaces. This study’s findings are limited to controlled waterfront environments. Long-term exposure to high humidity (e.g., coastal regions) may accelerate material degradation, necessitating hydrophobic coatings. Future applications could adapt these designs to indoor galleries using miniaturized actuators or urban plazas with reinforced anchoring systems for wind resilience.

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