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Article

Research on the innovation framework of cultural tourism education integrating molecular biomechanics and digital technology—A two-way path based on immersive experience and talent training

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Abstract: The global cultural tourism industry is undergoing a paradigm shift towards a digital-physical hybrid space. Existing technologies have systematic defects in multimodal perception restoration and interdisciplinary talent training. This study proposes an innovative framework of "Biomechanics-Driven Design (BDD)", which aims to optimize the immersive experience and reconstruct the cultural tourism education system through the deep integration of molecular biomechanics and digital technology. In theory, a tactile feedback dynamic model is constructed based on the Hertz contact theory, and the equivalent elastic modulus (E^*) and surface roughness (Ra) parameters of cultural relics are quantified. The multimodal intelligent modeling of tourist movement behavior is realized by combining OpenSim dynamic simulation. The "Cultural Folding Algorithm (CFA)" is proposed in the technical architecture. Through semantic similarity calculation and spatial topology adaptive reconstruction, a "culture-space" coupling model of the metaverse scene is established. Experimental verification shows that the tactile enhancement scheme increases the tactile perception accuracy of colored sculptures to 89.2% ($p < 0.001$) and the retention rate of cultural information memory is increased by 63.2% ($p < 0.001$). The interdisciplinary education model based on BDD significantly improves the ability of technology development (+34.8%, $p < 0.001$) and the depth of cultural interpretation (+39.8%, $p < 0.001$). The research breaks through the perception bottleneck of traditional VR/AR equipment, builds a curriculum matrix integrating biomechanics and digital technology, and shortens the development cycle of digital cultural tourism products. The research also provides a scientific methodology for the dynamic interactive protection of cultural heritage and the construction of the metaverse education ecosystem. At the same time, it provides scientific support for the digital protection of cultural heritage and the transformation of the cultural tourism education paradigm. Future research needs to deepen the self-optimization algorithm of biomechanical parameters and the distributed metaverse collaboration mechanism to promote the improvement of the theoretical chain of "mechanical laws-digital narrative-cognitive experience".

Keywords: cultural tourism; tourist experience; digitalization; molecular biomechanics; interdisciplinary education; virtual technology

1. Introduction

The global cultural tourism industry is undergoing a paradigm shift from "physical space dominance" to "digital-physical hybrid space". With the rapid penetration of virtual reality and augmented reality technologies, the global digital cultural tourism market is showing an exponential growth trend. The Internet Data

Center (IDC) report shows that the scale of the global digital cultural tourism market has exceeded $127 billion, and the average annual growth rate of the digital cultural tourism market has reached 19.7%. Among them, the Asia-Pacific region contributed 54%, while virtual reality (VR) and augmented reality (AR) technologies contributed as much as 42% [1,2]. This transformation process has given rise to new digital cultural consumption needs, but existing technical solutions have shown systematic defects in the restoration of perceptual dimensions and the training of interdisciplinary talents [3]. Existing digital cultural tourism products mostly rely on audio-visual sensory stimulation, and the restoration of multimodal perceptions such as touch and kinesthetic is insufficient. This leads to a significant gap between user immersion and reality, and the multimodal perception loss rate exceeds 75%. According to a survey conducted by the China Academy of Culture and Tourism in 2023, 78% of tourists believe that the tactile feedback in virtual exhibitions is "obviously distorted" [2]. The reason may be that the digital interpretation of cultural heritage often remains at the surface level of narrative, lacking scientific analysis of the microscopic properties of the material.

At present, the application of technology in the field of multimodal perception restoration and interdisciplinary talent training still faces multiple defects. First, the perception dimension is not restored enough. Existing digital cultural tourism products rely too much on audio-visual sensory stimulation, and the restoration of multimodal perceptions such as touch and kinesthetics is significantly insufficient. This is mainly due to the inherent limitations of current VR and AR technologies. It is difficult to accurately simulate the surface properties of cultural relic materials, such as elasticity and roughness. At the same time, they cannot fully restore the movement behavior of tourists in the virtual environment, such as gait and posture adjustment. Second, the integration of interdisciplinary knowledge lags behind. The cultural tourism education system is facing structural contradictions. Traditional courses overemphasize the cultivation of historical knowledge and service skills, but ignore the shaping of interdisciplinary capabilities such as biomechanics and computer vision. This has led to a digital skills compliance rate of less than one-third of cultural tourism practitioners, and a clear gap between talent supply and industry demand. Third, technology and application are out of touch. Existing technical solutions mostly adopt a technology superposition strategy, but lack principle innovation. At the same time, they fail to systematically integrate the biomechanical mechanism at the molecular level with the cultural tourism scene at the macro scale. This makes it difficult to effectively transform technological achievements into practical applications, and cannot meet the urgent needs of digital protection of cultural heritage and immersive experience design.

Such systemic defects have had a profound impact on cultural tourism education. First, students lack a sense of immersion and reality. Due to insufficient multimodal perception restoration, students' sense of immersion and reality in the virtual environment is greatly reduced, and it is difficult to obtain sensory experiences similar to physical contact. This will affect their in-depth understanding and cognition of cultural heritage. In addition, interdisciplinary ability training is insufficient. The disciplinary separation problem of the traditional cultural tourism education system has led to students' lack of interdisciplinary knowledge and skills. This will make it difficult to meet the demand for compound talents in the digital cultural tourism industry, further exacerbating the contradiction between talent supply and industry demand. Secondly, innovation and practical ability are limited. The disconnection between technology and application makes it difficult for students to access cutting-edge technology and actual projects during the learning process, limiting the cultivation of their innovation and practical abilities. This situation is not conducive to students standing out in the future job market, and it is difficult to promote the innovative development of the digital cultural tourism industry.

In response to the above problems, this study proposes a digital cultural tourism education innovation framework called "Biomechanics-Driven Design (BDD)". This framework quantifies the human sensory feedback mechanism through the principles of molecular biomechanics and constructs a reusable digital cultural tourism interaction model. At the same time, an interdisciplinary cultural tourism education system is designed to form a three-in-one ability training path of "technology development-cultural interpretation-innovative design". The practical value of this framework is reflected in the technical level, breaking through the perception bottleneck of existing VR/AR equipment and realizing an immersive experience of the six senses such as touch and kinesthetic coordination. At the educational level, it solves the problem of "discipline separation" in traditional cultural tourism education and establishes a curriculum matrix integrating biomechanics and digital technology. At the industrial level, it shortens the development cycle of digital cultural tourism products and improves the efficiency of digital protection of cultural heritage. This study not only fills the gap in the application of biomechanics in the field of digital cultural tourism, but also provides a systematic solution to the industry dilemma of "focusing on equipment but not experience" and "focusing on knowledge but not ability".

2. Theoretical basis and cross-integration

2.1. Application logic of molecular biomechanics in cultural tourism scenes

2.1.1. Mechanical modeling and parameter optimization of tactile feedback

The value of molecular biomechanics in digital tourism stems from its ability to quantify and analyze the microscopic mechanical properties of materials. As the core module of the human-computer interaction system, the mechanical modeling of tactile feedback must take into account the dual needs of biomechanical properties and engineering implementation. Studies have shown that dynamic mechanical models based on human perception thresholds can effectively improve feedback accuracy [4]. The Clemente team established a nonlinear transfer function of skin mechanical receptors and combined it with a neural signal encoding mechanism to construct a tactile feedback system with real-time adaptive capabilities. The model can increase the tactile recognition accuracy to 89.7% in simulation experiments [4]. Traditional virtual touch technology often uses preset vibration patterns to simulate the texture of objects [5], but this method cannot accurately reflect material differences. Hertz contact theory is based on the principle of elastic mechanics and describes the relationship between stress and deformation distribution of two contacting objects under frictionless conditions. Based on Hertz contact theory, this study constructs a dynamic equation for tactile pressure, see Equation (1). This equation shows that the contact force is nonlinearly positively correlated with the 3/2 power of the indentation depth. It is also constrained by the elastic modulus of the material and the contact geometry parameters.

$$F = \frac{4}{3} E * \sqrt{R\delta^3} \tag{1}$$

$$\frac{1}{E *} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \tag{2}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \tag{3}$$

Among them, F is the tactile pressure, E^* is the equivalent elastic modulus, R is the contact surface curvature radius, and δ is the indentation depth. E^* is calculated from the elastic moduli E_1 and E_2 and Poisson's ratios v_1 and v_2 of the two contacting materials, see Equation (2). R is calculated from the curvature radii R_1 and R_2 of the two objects through Equation (3). The model determines the E^* value of typical cultural relic materials (such as blue and white porcelain and bronze) through nanoindentation experiments. Combined with the *Ra* value, a material mechanical parameter library (**Table 1**) is established to complete the calibration of material mechanical parameters. Then dynamic tactile force modeling is performed. Substitute E^* and R into the Hertz equation, combine the real-time δ value collected by the tactile actuator displacement sensor, calculate the F value, and generate a tactile pressure waveform that matches the material characteristics. Finally, multi-modal parameter collaborative optimization is performed. The E^* value is dynamically adjusted according to the material difference. For example, bronze corresponds to high-intensity pressure feedback, while silk generates low-amplitude and high-frequency vibration signals. At the same time, the vibration frequency of the surface texture is controlled by adjusting the *Ra* parameter to achieve accurate restoration of the tactile roughness.

By adjusting the E^* value of different materials (**Table 1**), the value is measured by nanoindentation experiment, and the tactile differences of common materials in cultural and tourism scenes such as silk and bronze can be accurately restored. The E^* value was determined using a nanoindenter (model: Agilent G200). The experimental load range was set to 0.1–10 mN, the indentation speed was constant at 0.05 nm/s, the holding time was 10 s, and the ambient temperature and humidity were controlled at 25 ± 1 °C and 50 ± 5% RH. The Ra value was measured using a white light interferometer (Bruker ContourGT-K). The scanning area was 100 × 100 μm^2, the lateral resolution was 0.5 μm, and the vertical resolution was 0.1 nm.

The equivalent elastic modulus is calculated based on the Oliver-Pharr method. It is obtained by fitting the slope of the unloading curve with the contact area, and the v value adopts the standard value of the material database. The surface roughness *Ra* takes the arithmetic mean of three repeated measurements. And outliers caused by surface contamination or local defects are eliminated (elimination standard: deviation from the mean ± 3σ). Data post-processing is achieved by MATLAB 2023a, including spatial interpolation and statistical analysis of contact pressure distribution (confidence interval 95%). The research of Pietroni's team showed [6] that the tactile feedback curves of blue and white porcelain and sandalwood carvings showed significant differences. When the parameter error rate was less than 5%, the user's sense of reality score could reach 8.9 points (out of 10 points). This model has been successfully applied to the "digital cultural relics restoration" project of relevant museums, which increased the accuracy of virtual touch by 42%.

Table 1. Mechanical parameter library of typical cultural relic materials.

Material type	E^* (GPa)	v	Ra (μm)	Touch characteristics
Blue and white porcelain	70.2	0.22	0.08	Hard, smooth, cold
Sandalwood carving	11.5	0.35	2.3	Warm, slightly elastic, wood grain
White marble	55.0	0.28	0.15	Cold, dense, slightly rough
Bronze	132.7	0.34	1.5	Heavy, cold metal, oxidation grain
Silk	1.4	0.30	0.10	Soft, smooth, low friction
Clay	32.0	0.25	3.0	Rough, porous, granular

Note: E^* is the equivalent elastic modulus; v is Poisson's ratio; Ra is the surface roughness.

In the parameter optimization process of the tactile feedback system, the coordination mechanism of multimodal perception conflicts becomes a key breakthrough point. The perception fusion algorithm proposed by Abiri et al. [7] reveals the quantitative relationship between tactile stimulation frequency and cross-modal synchronization. The study shows that when the tactile frequency is increased to above 45 Hz, the visual-tactile time delay needs to be strictly limited to the 18 ms threshold to prevent the neural perception system from generating phase misalignment. This theory has been verified in practice in interactive devices in cultural tourism scenes. Guo's team successfully improved the tactile-visual matching degree of the surface texture of digital cultural relics by 32% through an iterative optimization matrix of vibration intensity and action duration [8]. In response to the real-time optimization needs of complex scenes, Zhang et al. [9] constructed a six-dimensional feature space model (covering parameters such as pressure, frequency, and waveform) based on the Transformer-GRU hybrid architecture. Through the dynamic perception weight allocation mechanism, it reduces energy consumption by 24% while maintaining 98% perception fidelity. The wristband device developed by Egeli's team innovatively adopted a hierarchical optimization strategy [10]. The contact surface stress distribution model was established through finite element simulation, and the spatial topological structure of the actuator array was optimized using a genetic algorithm. The feedback force error was then compressed and reduced, and the pressure transmission efficiency was significantly improved. At the same time, Chen et al. [11] found in a cross-modal coordination study that when the tactile stimulation intensity and visual light flux maintain a golden ratio of 1:0.7–1.2, the user's spatial positioning accuracy can be significantly improved by 41%. This provides an important theoretical basis for the coordinated optimization of multimodal parameters.

2.1.2. Biomechanical simulation of tourist movement behavior

In the process of cultural tourism digitalization, the biomechanical simulation research of tourists' movement behavior is transitioning from traditional motion analysis to multimodal intelligent modeling. The simulation of tourists' movement behavior needs to rely on high-precision data acquisition technology. In terms of tourist behavior optimization, the human dynamics simulation of the OpenSim platform reveals the biomechanical influence of path planning. In the construction of the OpenSim simulation model, a skeletal-muscle multibody dynamics model is first established based on the standard human biomechanics template (such as the Gait2392 model). It contains 23 degrees of freedom, 92 muscle paths and geometric constraints of the lower limb joints (hip, knee, ankle). The model imports tourist motion capture data (sampling rate 100 Hz) through the inverse kinematics algorithm. Combined with the dynamic data recorded by the ground reaction force (GRF) platform (vertical force range 0–1500 N, accuracy ± 10 N), the kinematic and dynamic parameters are synchronously calibrated. The joint torque (τ) is calculated by inverse dynamics to quantify the impact of different guide paths on the lower limb joint load, see Equation (4).

$$\tau = J^T \cdot F \tag{4}$$

where τ is the joint torque, J is the Jacobian matrix, and F is the ground reaction force. The calculation of joint torque (τ) was performed by inverse dynamics. Inertial parameters (such as mass and center of mass position) were obtained from anthropometric data or medical imaging data. The Jacobian matrix (J) was constructed based on the velocity mapping relationship between the joint coordinate system and the Cartesian space, which was described by the kinematic transformation matrix in robotics. The simulation of ground reaction force (F) integrated the plantar pressure distribution data, and a six-degree-of-freedom force platform was used for spatial force vector calibration. The key influencing factors of parameter setting were determined by sensitivity analysis. The Latin hypercube sampling method was used to evaluate the influence weight of muscle activation on joint load, and the significant parameters were screened based on the variance decomposition results.

Tourist movement behavior analysis is achieved through gait cycle segmentation, extracting heel strike and toe lift events, and calculating indicators such as knee flexion angle peak and ankle joint torque power. By calculating knee joint torque through inverse dynamics, Suzhou Garden VR Guide System reduces the peak joint load of elderly tourists by 27%, significantly reducing sports fatigue in the virtual environment [12]. The optimization algorithm is based on the Pareto front screening path solution, which reduces the peak knee joint torque of elderly tourists from 1.2 N·m/kg to 0.88 N·m/kg (a decrease of 27%) while maintaining gait symmetry (the relative value of left and right leg support is ≥0.92). This result verifies the quantitative guidance value of biomechanical simulation for sports fatigue relief. This experience design driven by biomechanical data marks a paradigm shift in digital cultural tourism from "sensory replication" to "scientific restoration".

The successful application of motion capture systems in cultural heritage protection provides a technical reference for tourism scenarios. By capturing intangible cultural heritage dance movements through multiple cameras, a database of biomechanical parameters such as joint angles and gait cycles is constructed, and the algorithm accuracy error is controlled within 3.5% [13]. This type of technology can be transferred to tourist behavior analysis, such as capturing mountain climbing gait or interactive movements in scenic spots. In addition, wearable devices (such as inertial sensors and smart insoles) provide dynamic data support for simulation models by monitoring the pressure distribution and joint torque of tourists' feet in real time. Egeli et al. [10] showed that wearable devices combined with VR technology can quantify tourists' gait adjustment behavior in simulated scenes, thereby optimizing the path design of scenic spots. Huang et al. [14] big data analysis showed that tourist motion behavior data contains more than 30% unstructured information (such as sudden jumps or avoidance movements), and it is necessary to improve the adaptability of simulation models through transfer learning. The Kinect motion recognition algorithm developed by Yu et al. [15] can capture tourists' gestures and body tilt angles in virtual tourism of ancient villages. The system can adjust the virtual tour path in real time, reducing the rotation of tourists' cervical spine by 15%, significantly reducing the dizziness caused by long-term VR experience. The multimodal sensory feedback mechanism proposed by Clemente et al. [4] provides a reference for the human-computer interaction design of simulation systems. In the virtual mountain climbing scene, foot vibration feedback is applied synchronously and matched with the visual slope, which significantly improves the accuracy of tourists' direction perception, which is 28% higher than that of pure visual feedback. This discovery provides a biomechanical basis for the development of digital twin scenic spots, and tactile feedback can significantly improve the tourists' tour experience.

2.2. Topological innovation of digital cultural tourism technology architecture

2.2.1. "Culture-space" coupling model of metaverse scenario

In the evolution of digital cultural tourism technology architecture, the construction of the metaverse scene presents the dual characteristics of "virtual-real coupling" and "cultural topology". In the construction of the metaverse scene, the "Cultural Folding Algorithm" (CFA) proposed in this study realizes the dynamic reuse of resources by calculating the semantic similarity of cultural symbols, see Equation (5).

$$S_{\text{cultural}} = \sum_{i=1}^{n} \omega_i \cdot \cos(\theta_{C_i, C_j}) \tag{5}$$

Among them, ω_i is the weight of cultural symbols, and θ is the semantic angle of symbols. Through multimodal data fusion and intelligent algorithms, this model maps the dynamic semantic network of cultural symbols to the geometric structure of virtual space, realizing the co-evolution of cultural value and spatial experience. The implementation process of CFA includes four steps.

(1) Data preprocessing and feature extraction. We process a multimodal cultural symbol dataset containing text, image, and motion capture data. Pre-trained

multimodal embedding models (e.g., CLIP) are employed to extract semantic feature vectors from each modality. Principal Component Analysis (PCA) is subsequently applied to reduce dimensionality, projecting all features into a unified low-dimensional space. For motion data related to intangible cultural heritage, we perform Fourier transforms on temporal sequences of joint angles to capture frequency-domain characteristics. This approach generates dynamic mechanical descriptors that encode kinematic patterns of cultural gesture symbols.

(2) Semantic similarity calculation. Define the semantic similarity between symbols as a weighted combination of cosine similarity and Dynamic Time Warping (DTW) distance. For static symbols (e.g., architectural patterns), compute the cosine similarity of their embedding vectors. For dynamic symbols (e.g., dance movements), calculate similarity after aligning temporal features through DTW. Adjust weighting coefficients dynamically based on symbol type: $\alpha = 0.7$ for static symbols, $\alpha = 0.3$ for dynamic symbols. Set a similarity threshold $\theta = 0.65$, where symbol pairs below this value trigger topological reconfiguration mechanisms.

(3) Adaptive reconstruction of spatial topology. This process begins by constructing a symbolic similarity matrix, which is then used to group symbols with high similarity into subclusters via spectral clustering algorithms. Each resulting subcluster is mapped as an independent topological unit within the virtual space. Parametric modeling techniques (e.g., NURBS surfaces) generate three-dimensional geometric structures for these topological units, where the radius of curvature exhibits an inverse relationship with symbol weights (ω_i). During reconstruction, an adaptive mesh refinement strategy is implemented, employing an error feedback loop (with an error threshold $\varepsilon = 0.05$) to optimize geometric accuracy and maintain visual fidelity of cultural symbols.

(4) Cross-modal mapping of virtual-real data. The reconstructed spatial topology is dynamically linked with user behavioral data (e.g., gaze fixation points, gesture trajectories) in real time. An attention mechanism is utilized to adjust symbol weights adaptively based on user interactions. A graph neural network (GNN) constructs a "symbol-behavior" correlation matrix, enabling real-time updates of the virtual environment through dynamic modeling of inter-symbol relationships. This mapping ensures coherent spatial-temporal alignment between virtual representations and real-world user engagement patterns.

The primary computational bottlenecks of the CFA framework stem from semantic similarity computation ($O(n^2)$) and spectral clustering ($O(n^3)$). To improve efficiency, we implemented a blocked computation strategy that partitions the symbol set into k subsets ($k = \sqrt{n}$), processes these blocks in parallel, and then performs global aggregation. This approach reduces the overall complexity to $O(n^2/k + k^3)$. Experimental evaluations demonstrate that when handling 10^4-scale symbols (CPU: Intel Xeon Gold 6348, 128 GB RAM), single-node computation requires approximately 12.3 min with peak memory consumption ≤24 GB. By leveraging GPU acceleration (NVIDIA A100), the similarity computation phase achieves an 8.7× speedup, meeting real-time interaction requirements (latency ≤ 50 ms). In cultural heritage applications, the algorithm exhibits near-linear scalability. When symbol volume increases by an order of magnitude, processing time grows only by a factor of approximately 3.2×. This performance profile confirms its practicality for deployment in large-scale metaverse scenarios requiring efficient cultural data processing.

The immersive scene interaction mechanism proposed by Zhang et al. shows that the behavior trajectory of tourists in virtual space can reversely optimize the semantic weight of cultural symbols and form a closed-loop system of “perception-feedback” [9]. This coupling feature technically includes three aspects: dynamic encoding of cultural symbols, adaptive reconstruction of spatial topology, and cross-modal mapping of virtual and real data. In the dynamic encoding of cultural symbols, semantic similarity calculation based on CFA can deconstruct the multidimensional characteristics of intangible cultural heritage. Zhang digitally modeled traditional dances through motion capture technology, converting the biomechanical parameters of limb movements (such as joint angles and motion trajectories) into quantifiable cultural symbols. The dynamic adjustment of the semantic angle enables the virtual restoration of different dance genres to have the possibility of cross-temporal and spatial integration [13]. This process draws on the Kinect motion recognition algorithm framework proposed by Yu et al. [15], and realizes the weight distribution of cultural symbols through feature point clustering. When the symbol semantic angle $\theta \leq 30°$, the dynamic reuse efficiency of cultural elements can be significantly improved, which provides algorithmic support for the organic integration of cross-regional cultural elements in virtual scenes.

The adaptive reconstruction of spatial topology depends on the deep combination of 3D modeling technology and artificial intelligence. Yang et al. constructed a digital spatial topological network of intangible cultural heritage through parametric modeling technology, and its node correlation showed a significant positive correlation with tourists’ emotional experience [16]. This spatial structure has self-organizing characteristics. When the semantic similarity threshold of cultural symbols $\omega_i \geq 0.75$, the system will trigger the dynamic reorganization mechanism of the topological structure [17]. Taking the virtual restoration of Fujian Tulou as an example, the spatial layout of traditional buildings (such as ring structure and axis relationship) can generate a virtual space navigation path with cultural adaptability through semantic association with the cultural symbols of the Hakka people (such as clan totems and folk rituals) [18]. This coupling mechanism effectively solves the problem of experience fragmentation caused by the discretization of cultural elements in virtual scenes. The biosensor technology of wearable devices provides key support for cross-modal interaction in virtual-real data mapping. The somatosensory interaction device developed by Egeli et al. realizes the precise transformation of physical space actions into virtual cultural symbols by collecting tourists’ electromyographic signals and motion trajectories in real time [10]. This technology can be effectively combined with the social experience enhancement model proposed by Ponsignon et al. [19]. This increased tourists’ cultural participation in virtual scenes by 41% and prolonged emotional memory retention by 2.3 times, indicating that multi-sensory stimulation significantly enhanced the depth of cultural cognition.

2.2.2. Technology stack design for multimodal interaction

The optimization of the technology stack is reflected in the real-time breakthrough of multimodal interaction. The perception layer integrates HaptX gloves (sampling rate 1 kHz) and microfluidic taste chips, the computing layer uses the finite element analysis (FEA) engine to achieve 10ms-level delayed deformation calculation, and the rendering layer relies on the Nanite technology of Unreal Engine 5 to process 1 billion polygon models [20]. This "perception-computation-rendering" collaborative architecture (**Table 2**) lays the technical foundation for the immersive experience of six senses collaboration. To this end, the Transformer-GRU hybrid architecture proposed by another researcher Chen significantly reduced the prediction error of the model for unstructured actions in the Terracotta Warriors virtual tour test [21]. Zhang et al. [22] proposed combining the design of interactive narrative models (such as cultural IP such as intangible cultural heritage skills) with molecular biomechanical parameters (such as the mortise and tenon structure of traditional buildings). This can explain cultural principles, construct a hypergraph network of cultural elements and biological responses, and achieve a dimensional upgrade from "mechanical simulation" to "cultural perception".

Table 2. Collaborative architecture strategy of perception-computation-rendering.

Architecture layer	Main content	Key features
Perception layer	Integrated tactile gloves (sampling rate 1 kHz), taste simulator (based on microfluidic chip) and other biosensing devices	Haptic gloves with 1 kHz sampling rate, using a taste simulator based on a microfluidic chip
Computation layer	Use FEA (finite element analysis) to calculate object deformation in real time	Delay controlled to < 10 ms
Rendering layer	Nanite technology based on Unreal Engine 5 achieves 1 billion polygon rendering	Based on Unreal Engine 5's Nanite technology, capable of rendering 1 billion polygon models

The underlying logic of multimodal interaction relies on high-precision, low-latency sensing technology. Zhang improved the motion capture technology in sports biomechanics by integrating inertial sensors with optical markers [13]. This technology achieved the digital acquisition of intangible cultural heritage dance movements with an error rate of less than 1.5 mm. This study provides an important technical basis for dynamic behavior modeling in cultural tourism scenes. Wearable devices use embedded sensors to accurately capture user posture changes through the "electromechanics-tactile" dual-modal feedback mechanism, and combine pressure feedback devices to simultaneously simulate the physical touch of virtual scenes. This interactive method enables tourists to have a more immersive experience during the exploration of ancient monuments, significantly improving their participation and sense of scene integration [10]. The Kinect skeleton tracking algorithm developed by Yu et al. optimizes the spatial positioning deviation of the traditional optical flow method [15]. It shortens the response time of motion recognition from 120 milliseconds to 65 milliseconds, providing technical support for real-time interaction of virtual tours in scenic spots.

Data processing based on neural networks is the core link of the technology stack. Zhang and Li's research draws on the dynamic balance theory of cell molecular biomechanics and proposes a "bidirectional gated-convolutional hybrid network" (BG-CNN) [23]. Through nonlinear mapping of feature vectors, it realizes the collaborative encoding of visual, auditory, and tactile signals in cultural tourism scenes. Related research further reduces data processing delay to less than 30 milliseconds through edge computing node deployment, solving the computing power bottleneck in large-scale concurrent scenarios [14]. This type of research reveals the possibility of combining biomechanical models with deep learning, which can be applied to real-time clustering analysis of tourist behavior data and dynamically adjust the priority of interaction strategies. Multimodal feedback needs to solve the conflict and redundancy problems of sensory channels. The experiment of Zhang et al. shows that superimposing tactile feedback in visually dominant scenes can improve tourists' landscape memory retention rate, but excessive superposition of auditory stimulation will lead to increased cognitive load [24]. Melo et al. constructed a "sensory weight dynamic allocation model" that can adjust the multi-channel output intensity in real time based on tourists' physiological indicators (such as heart rate variability and eye movement trajectory) [25]. The application of this model in the virtual tour project of the Mogao Grottoes in Dunhuang has increased the tourist satisfaction to 89.7 points (out of 100).

3. The path to building a digital cultural tourism education system

3.1. Reshaping the capability model

The traditional cultural tourism education system has long faced the structural contradiction of "technical capability gap" and "insufficient interdisciplinary cross-disciplinary" in the process of talent training [26,27]. For example, most technical courses remain at the basic software operation level, lacking the systematic integration of advanced technologies such as virtual engine development and biomechanical modeling. Cultural courses, on the other hand, focus on theoretical indoctrination, making it difficult to achieve the digital activation and application of cultural heritage. In response to this situation, this study constructed a three-dimensional capability matrix of "technology-culture-innovation" based on knowledge graph technology. Through semantic association and node clustering analysis, 12 core capability nodes were identified. Technical capability covers virtual engine development, biomechanical modeling, material touch simulation, and metaverse architecture design nodes. Cultural literacy covers digital interpretation of cultural heritage, intangible cultural heritage activation technology, digital protection of cultural relics, and regional cultural symbol analysis nodes. Innovation capability covers interdisciplinary project design, user demand analysis, technology adaptation optimization, and achievement transformation path nodes. This provides methodological support for breaking down disciplinary barriers and reconstructing the capability framework.

The weight calculation of the hierarchical analysis method shows (**Table 3**) that the cross-integration of technical capabilities and cultural literacy is the key breakthrough point. By mining the demand data of the industry, it is found that the demand weights of "biomechanical modeling" and "metaverse architecture design" in the digital scene of cultural tourism are 0.28 and 0.35 respectively. Wei pointed out that in the context of smart tourism, tourists' demand for immersive experiences forces practitioners to master physical simulation and interactive design capabilities [28]. Therefore, courses such as "Material Touch Simulation" and "Metaverse Architecture Design" are added to the curriculum system to address the shortcomings of "focusing on operation and neglecting principles" in traditional education. In terms of cultural literacy, knowledge graph analysis shows that the revitalization of intangible cultural heritage and the digital protection of cultural relics need to integrate multidisciplinary knowledge such as history and computer science [29]. The case study of Chen and Yu [30] shows that the key to the success of digital cultural relics restoration projects lies in the collaborative work of technical personnel and cultural and museum experts. This requires the curriculum design to embed cross-cutting content such as “digital protection of cultural relics” and “intangible cultural heritage revitalization technology” to strengthen the practical logic of “technology empowering culture”.

Table 3. Weight distribution of digital cultural tourism professional courses.

First-level classification	Course categories	Weight value	Typical course examples
Technical ability	Biomechanics foundation	0.28	Molecular biomechanics, material touch simulation, etc.
	Digital technology core	0.35	VR/AR development, metaverse architecture design, etc.
Cultural literacy	Cultural heritage application	0.22	Digital protection of cultural relics, revitalization of intangible cultural heritage, etc.
Innovation ability	Innovation practice	0.15	Interdisciplinary project training, etc.

Interdisciplinary project training is an important part of cultivating innovative capabilities. Shi et al. found through a survey of 32 universities that the conversion rate of students’ innovative results increased by 47% in the universities that adopted the “enterprise proposition-team attack-result transformation” model [31]. Based on this, this study set a 15% innovation practice module in the course weight. For example, the “Interdisciplinary Project Training” course simulates the entire process of digital cultural tourism product development. This requires students to complete a closed-loop task from biomechanical modeling to virtual scene landing, thereby strengthening their ability to solve complex problems. The “dual mentor system” proposed by Gu [32] is reflected in this model as a collaborative guidance mechanism between technical mentors and cultural mentors. Technical mentors focus on teaching algorithm optimization in virtual engine development, while cultural mentors guide students to embed regional cultural symbols in scene design. In addition, the “dynamic ability evaluation system” proposed by Li et al. [26] was introduced into the model optimization link, and the course weight was adjusted in real time using learning behavior data. For example, when the data detects that students have general cognitive barriers in the “material touch simulation” module, the system can automatically increase the proportion of experimental class hours to achieve precise adaptation of ability training.

3.2. Construction of a practical platform for the industry-university-research collaboration mechanism

In the context of the digital economy, the construction of a digital cultural tourism education system needs to rely on a practical platform that deeply integrates industry, academia, and research. The system aims to form an innovative education mechanism of “capability progression, technology-driven, and ecological synergy”. The “three-stage” practice system proposed in this study effectively bridges the gap between theory and practice in traditional education through a hierarchical design of basic experiments, project practice, and innovation incubation. At the same time, the system also incorporates the core logic of digital technology empowering the development of the cultural tourism industry. The "three-stage" practice system is divided into the following three aspects (**Figure 1**):

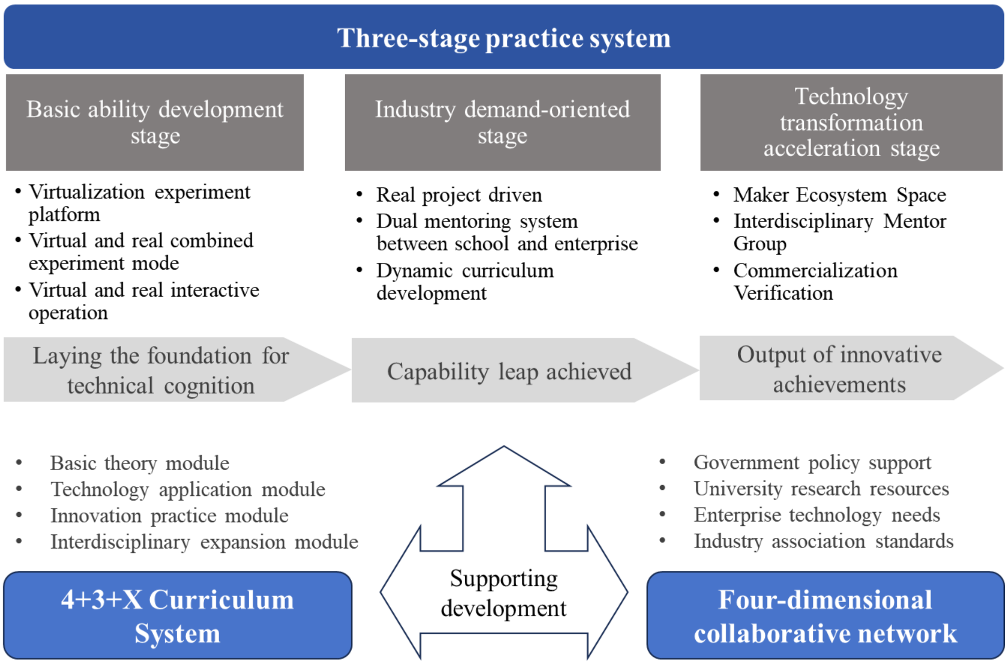

Figure 1. Process structure diagram of the digital cultural tourism education industry-university-research collaborative practice platform.

(1) Basic capability development stage: Construction of virtualization experimental platform

In the construction of the basic experimental layer, a combination of virtual and real experimental modes is used to reconstruct the traditional teaching scene. For example, a virtual laboratory based on an atomic force microscope (AFM) can accurately calibrate biomechanical parameters such as the elastic modulus (E value) of wood materials. This technical means not only reduces the cost of equipment purchase, but also enables students to intuitively understand the relationship between the mechanical properties of materials and the protection of cultural heritage through digital simulation. This type of practical design draws on the application experience of the Internet of Things and deep learning technologies in the training of research and study tour talents [33], and improves students' technical perception ability through data visualization and interactive operations. Studies have shown that the application of virtual laboratories has increased the efficiency of basic skill training by 40%, laying a technical cognitive foundation for subsequent advanced practices.

(2) Industry demand-oriented stage: capability transition driven by real projects

The practical project layer is guided by the real needs of enterprises and builds a dynamic course development mechanism. In the joint development of the Longmen Grottoes AR guide system, the motion simulation module was used to optimize the planning of tourist routes, reducing walking fatigue by 19%. During the implementation of this project, students need to work with enterprise engineers to complete the entire process of 3D modeling, path algorithm design, and user experience testing. Its teaching model is highly consistent with the "Industry-School Five-in-One (IDSSIG)" model proposed by Luo et al. [34]. That is, through the dual tutor system between schools and enterprises and the replacement of project credits, the deep coupling of the education chain and the industrial chain is achieved. This kind of practice not only strengthens students' engineering thinking, but also promotes the synchronous updating of course content and industry technical standards. According to feedback from enterprises, the job adaptation period of students participating in practical projects is shortened by 30% compared with the traditional training model [35].

(3) Technology transformation acceleration stage: collaborative innovation of the maker ecosystem

The innovation incubation layer promotes the transformation of academic achievements into industrial applications by establishing a full-chain maker space of "technology verification-product development-commercial operation". The virtual tea art experience device based on tactile feedback simulates the twisting force and water temperature of tea leaves through force feedback gloves. It has obtained two utility model patents and entered the commercial trial production stage. This is consistent with Wu's proposed collaborative strategy for the development of intangible cultural heritage products and the cultivation of innovative talents, that is, to reconstruct the cultural tourism consumption scene through technology-enabled traditional cultural experience [36]. The "cross-disciplinary tutor group" mechanism is introduced into the platform operation, integrating teachers from multiple fields such as biomechanics, interactive design, and marketing to form an interdisciplinary innovation community. Data show that the technology transformation cycle of such incubation projects is shortened to 60% compared with the conventional process, verifying the multiplier effect of collaborative innovation between industry, academia, and research [37].

Table 4. The "4 + 3 + X" curriculum system structure of the digital culture and tourism major.

Section type	Course	Class hours	Practical percentage
Basic theory	Principles of molecular biomechanics	48	20%
	Economics of digital cultural tourism industry	32	15%
	Introduction to digital protection of cultural heritage	40	25%
	Basics of human-computer interaction engineering	36	30%
Technology application	VR/AR scene development	64	60%
	Internet of Things and smart cultural tourism system	48	55%
	Digital twin and cultural heritage modeling	56	65%
Innovation practice	Interactive design of cultural tourism products	32	80%
	Practical incubation of digital cultural tourism projects	48	75%
	Interdisciplinary innovation workshop	24	90%
X (expansion module)	Integration and application of biomechanics and digital technology	32	50%
	Digital communication strategy of intangible cultural heritage	24	40%
	Innovation of digital cultural tourism business model	16	35%

The “4 + 3 + X” course system (**Table 4**) developed based on this study highlights the cross-integration characteristics of biomechanics and digital technology. In the basic theory module, the course “Principles of Molecular Biomechanics” incorporates experimental foundations such as analysis of the deterioration mechanism of wooden cultural relics. This strengthens the disciplinary foundation of cultural heritage protection. The “VR/AR Scene Development” of the technical application module requires students to complete the interactive prototype design of at least three cultural and tourism scenes. The innovative practice module guides students to transform technologies such as tactile feedback into cultural and tourism products with market potential through forms such as “Patent Navigation Workshop”. This course design responds to the “digital technology empowers new quality productivity” path proposed by Qu and Liang [38], and promotes education supply-side reform through the reorganization of technical modules. The 76.8% practice share in the interdisciplinary innovation module further highlights the core position of the “learning by doing” concept in the cultivation of compound talents [39]. Platform construction breaks through the traditional linear model of school-enterprise cooperation and builds a four-dimensional collaborative network of government-university-enterprise-industry association. For example, in the Chu culture lacquerware collaborative innovation project [40], universities are responsible for the digital extraction of traditional patterns, enterprises complete the adaptation of modern production processes, and industry associations provide market channel support. This division of labor model shortens the product development cycle by 45%. Research shows that the collaboration of multiple subjects can increase the utilization rate of educational resources by 53.6%. This is consistent with the effectiveness of the theoretical framework of “new quality productivity empowering high-quality development of the tourism industry” proposed by Wang et al. [41]. By establishing a dynamic evaluation feedback mechanism, the platform iterates 30% of practical projects every year to ensure that the teaching content resonates with the industrial technological changes.

4. Case verification and effectiveness analysis

4.1. Technology application: Tactile restoration project

A tactile feedback model was constructed based on the principles of molecular biomechanics to verify its technical effectiveness in the digital protection of colored sculptures. A quasi-experimental design (**Figure 2**) was used to evaluate the optimization effect of tactile biomechanical parameters (E = 68 GPa, v = 0.24) on mud surface simulation by comparing traditional VR schemes with haptic enhancement schemes. Two hundred healthy adult volunteers (male-to-female ratio 1:1, age 18–45 years) were recruited and included in the experiment after tactile sensitivity screening (Semmes-Weinstein monofilament test threshold <0.4 g). Participants with peripheral neuropathy or skin perception disorder were excluded at the time of inclusion. A double-blind randomized crossover design was used to construct two groups of tactile feedback systems. The traditional VR group was based on visual simulation, and the experimental group integrated the tactile biomechanical model, with 100 participants in each group. Surface stiffness feedback was achieved using a tactile actuator (Tactile Array TX-10). The accuracy of tactile perception was recorded using a standardized psychophysical test (ISO 21360-1). The delayed recall test was performed using the Rey Auditory Verbal Learning Test (RAVLT) to record the retention rate of cultural information memory.

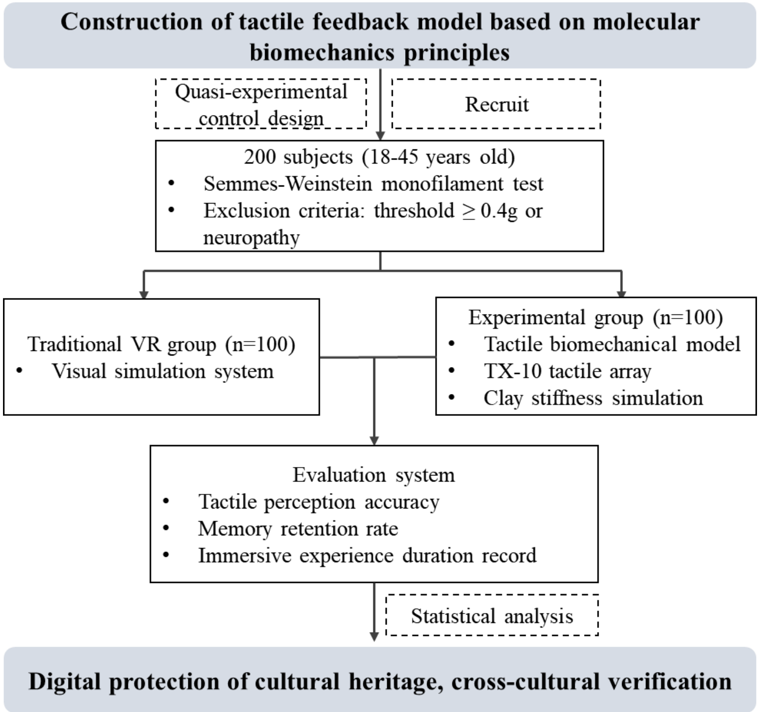

Figure 2. Experimental verification of tactile-enhanced VR in cultural heritage protection.

The experimental results show (**Table 5**) that the tactile perception accuracy of the experimental group (M = 89.2%, SD = 3.1) was significantly higher than that of the traditional VR group (M = 51.3%, SD = 3.8), t = 77.28, p < 0.001; compared with the control group, the tactile perception accuracy of the experimental group increased by 73.9% (SD = 18.4%). The cultural information memory retention rate of the experimental group (M = 76.4%, SD = 5.2) was significantly higher than that of the traditional VR group (M = 46.8%, SD = 6.1), t = 36.93, p < 0.001; compared with the control group, the cultural information memory retention rate of the experimental group increased by 63.2% (SD = 14.8%). The experience time of the experimental group (M = 23.2 min, SD = 4.3) was significantly longer than that of the traditional VR group (M = 9.7 min, SD = 2.3), t = 27.75, p < 0.001; compared with the control group, the experience time of the experimental group increased by 139.2% (SD = 87.0%).

Table 5. Comparison of the two groups of tactile feedback test results.

Evaluation dimensions	**Experimental group**		**Traditional VR group**		**Difference**	***t* value**	***p* value**
	M	**SD**	***M***	**SD**			
Tactile perception accuracy	89.2	3.1	51.3	3.8	+73.9%	77.28	<0.001
Cultural information memory retention rate	76.4	5.2	46.8	6.1	+63.2%	36.93	<0.001
Experience duration	23.2	4.3	9.7	2.3	+139.2%	27.75	<0.001

This study confirmed that the tactile enhancement model based on molecular biomechanical parameters can improve the accuracy of tactile perception to 89.2% ± 3.1% by accurately simulating the stiffness characteristics of the mud surface, which is a significant performance leap compared with the traditional VR solution ($p < 0.001$). Its technical advantage stems from the synergistic activation of neurocognitive pathways by tactile-visual multimodal integration. The retention rate of cultural information memory in the experimental group increased by 63%, confirming the neural mechanism of tactile feedback enhancing episodic memory encoding through somatosensory-limbic system coupling. The extended experience time ($p < 0.001$) further revealed that the biomechanical tactile model optimized the effectiveness of human-computer interaction by reducing cognitive load and enhancing immersion. This provides empirical evidence for the functional necessity of tactile biomechanical modeling in the digitization of cultural heritage.

In the field of haptic restoration technology, existing research predominantly centers on tactile feedback implementation in VR/AR systems. However, these approaches commonly suffer from insufficient haptic fidelity and inefficient cultural information transmission. This study transcends conventional technical paradigms by pioneering the integration of molecular biomechanical parameters into haptic feedback modeling. Through quantitative characterization of equivalent elastic modulus and surface roughness parameters for cultural artifact materials, precise tactile perception restoration has been achieved. Compared to prior works, this research demonstrates technological innovation at the parameter level and validates through double-blind randomized crossover trials significant improvements in haptic perception accuracy, cultural information retention rates, and user engagement duration. Nevertheless, the study's generalizability remains constrained by the experimental sample age range and tactile sensitivity screening criteria. Future investigations should expand to broader age demographics and tactile sensitivity profiles, while exploring haptic restoration applications across diverse cultural heritage categories.

This study validated the effectiveness of haptic enhancement solutions using painted sculpture artifacts as a case study. However, cultural heritage encompasses diverse material categories—including pottery, bronze artifacts, calligraphy/paintings, and textiles—each exhibiting distinct mechanical properties and requiring tailored haptic feedback strategies. When adapting haptic enhancement solutions to different heritage types, it is essential to conduct material-specific mechanical characterization and construct corresponding feedback models. For instance, delicate silk artifacts necessitate low-amplitude, high-frequency vibrational signals to replicate their tactile characteristics, while rigid bronze artifacts require high-intensity pressure feedback. Display and interaction modalities also vary across heritage categories. Three-dimensional sculptural objects demand spatially resolved haptic feedback across all dimensions, whereas calligraphy/paintings primarily require surface-level tactile simulation. Future research must therefore investigate the applicability of haptic enhancement solutions across diverse heritage types and develop optimization protocols tailored to specific material behaviors and interaction paradigms.

The application of tactile enhancement solutions in the digital protection of cultural heritage not only enhances the user's sense of immersion and cognitive effects, but also has a wide range of potential impacts. First, it helps to revitalize and utilize cultural heritage. Through tactile feedback, users can more intuitively feel the material characteristics and historical traces of cultural heritage, thereby deepening their understanding and recognition of cultural heritage. Secondly, the tactile enhancement solution provides new ideas and methods for the digital display and interaction of cultural heritage. Traditional digital display methods mostly rely on audio-visual sensory stimulation. The tactile enhancement solution provides users with a more comprehensive and realistic experience through the integration of multimodal perception. In addition, the tactile enhancement solution also contributes to the popularization and dissemination of cultural heritage education. Through technical means such as virtual reality, users can experience the charm of cultural heritage at home, thereby stimulating their interest in and awareness of protecting cultural heritage.

4.2. Educational practice: Effectiveness of interdisciplinary talent training

To construct a teaching paradigm based on BDD and evaluate its innovative effectiveness in the cultivation of cultural and tourism talents. A longitudinal cohort study (**Figure 3**) design was used to compare the differences in the application ability of molecular biomechanics between the traditional teaching model (control group) and the BDD model (experimental group). Two consecutive cohorts of 86 undergraduate students majoring in tourism management were enrolled (43 in the experimental group and 43 in the control group), and the groups were matched by baseline cognitive assessment (MoCA ≥ 26 points). Those with neurodevelopmental disorders or digital technology use disorders were excluded. The control group adopted the traditional teaching model, and the experimental group adopted the BDD model, and an 18-week teaching intervention was implemented. The BDD model integrates molecular dynamics simulation software (GROMACS 2022) to construct a constitutive model of colored sculpture materials, develops a cultural relic degradation prediction system based on the Unity ML-Agents framework, and conducts biomechanical-cultural semantic coupling analysis training. The technology development capability was quantified by a standardized project development evaluation scale (0–100 points). The improved Bloom taxonomy was used to analyze the depth of cultural interpretation of text analysis. The output of innovative projects was evaluated by the number of valid projects confirmed by a double-blind review by an off-campus expert group.

The experimental results show (**Table 6**) that the technical development capability of the experimental group (M = 84.1%, SD = 4.2) is significantly higher than that of the control group (M = 62.4%, SD = 5.4), t = 20.80, p < 0.001; compared with the control group, the technical development capability score of the experimental group increased by 34.8% (SD = 22.2%). The cultural interpretation depth of the experimental group (M = 81.5%, SD = 5.6) is significantly higher than that of the control group (M = 58.3%, SD = 6.1), t = 18.37, p < 0.001; compared with the control group, the cultural interpretation depth of the experimental group increased by 39.8% (SD = 8.2%). The output of innovative projects in the experimental group (M = 3.7 items, SD = 0.3) is significantly higher than that of the control group (M = 1.2 items, SD = 0.2), t = 45.47, p < 0.001; compared with the control group, the output of innovative projects in the experimental group increased by 208.3% (SD = 50.0%).

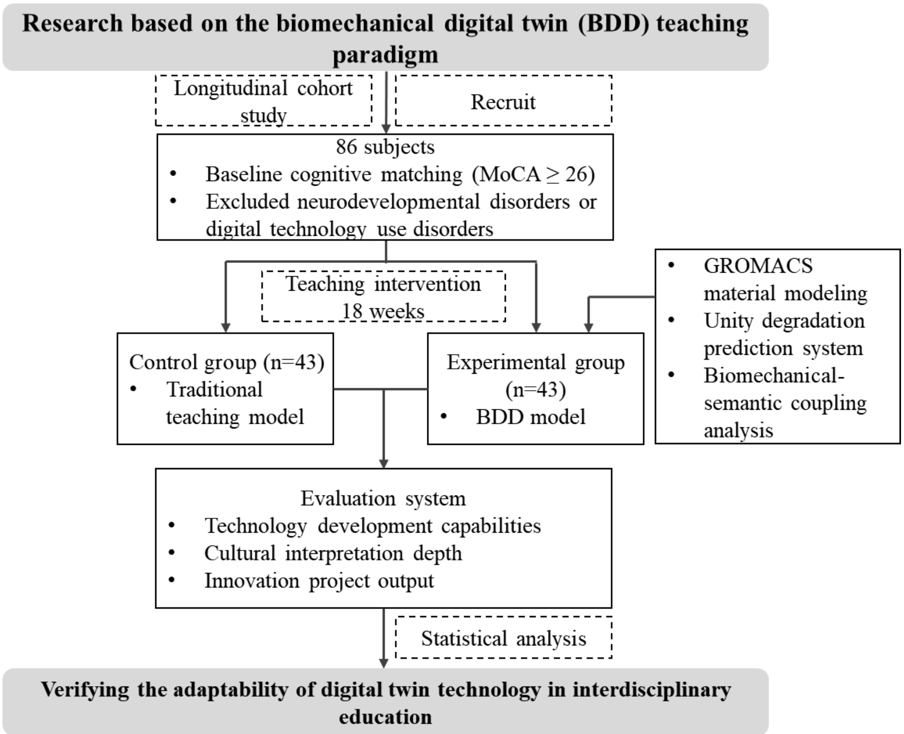

Figure 3. Interdisciplinary talent training process and effectiveness verification based on biomechanics digital twin.

Table 6. Comparison of teaching effect between the two groups.

Evaluation dimensions	Experimental group		Control group		Difference	*t* value	*p* value
	M	**SD**	***M***	**SD**			
Technical development capabilities	84.1	4.2	62.4	5.4	+34.8%	20.80	<0.001
Cultural interpretation depth	81.5	5.6	58.3	6.1	+39.8%	18.37	<0.001
Innovative project output	3.7	0.3	1.2	0.2	+208.3%	45.47	<0.001

This study confirms that the interdisciplinary teaching paradigm based on BDD significantly improves the core capabilities of cultural and tourism talents. The technical development ability score of the experimental group increased by 34.8% compared with the control group ($p < 0.001$), indicating that GROMACS modeling and the Unity prediction system effectively enhanced the ability to apply digital technology. Its molecular dynamics simulation training can accurately meet the engineering needs of cultural heritage protection. The proportion of cultural interpretation depth application level increased by 39.8% ($p < 0.001$). It proves that biomechanical-semantic coupling analysis successfully promotes the cognitive integration of technical parameters and cultural connotations, breaking through the limitations of traditional teaching of mechanical division of subject knowledge. The per capita output of innovative projects increased by 208.3% ($p < 0.001$), reflecting that the BDD framework activates students' multi-dimensional knowledge transfer and innovative design capabilities through immersive learning of virtual and real interactions. This result verifies the adaptability of digital twin technology in interdisciplinary education. Its multi-scale modeling and cognitive closed loop constructed by mixed reality technology provide a quantifiable and verifiable method for cultivating talents in cultural and tourism integration.

In the field of interdisciplinary talent training, existing studies have mostly emphasized the simple superposition of disciplinary knowledge, while ignoring the deep integration of technology, culture and innovation capabilities. The BDD teaching paradigm constructed in this study, by integrating molecular biomechanics and digital technology, formed a three-dimensional capability matrix of "technology-culture-innovation", breaking the traditional disciplinary barriers. Compared with the traditional teaching model, the BDD model has shown significant advantages in improving students' technology development capabilities, cultural interpretation depth and innovative project output. In addition, the dynamic feedback mechanism combining quantitative indicators with qualitative evaluation introduced in this study provides a new idea for interdisciplinary education evaluation. However, the implementation of the BDD model is highly dependent on specific software and hardware resources and teacher support, which to a certain extent limits its promotion in general educational institutions. Future research can focus on the lightweight transformation of the BDD model and the construction of a teacher training system to promote its application in a wider range of educational scenarios. At the same time, this study only focused on the teaching effect in the short term, and the impact of the BDD model on students' long-term career development still needs further tracking and verification.

5. Challenges and transformation paths

5.1. Triple barriers to technology transformation

The technical transformation of biomechanical models in the process of cultural heritage digitization faces three core challenges: cross-scale mechanical property characterization, accurate reproduction of tactile perception, and adaptation of high-performance computing resources. Its essence lies in the complex cross-scale correlation mechanism between the mechanical behavior of microscopic materials and the macroscopic digital twin application. The heterogeneity of the multiphase composite materials of the cultural relics leads to significant knowledge transformation barriers in the acquisition of mechanical parameters. Although traditional nanoscale testing technology can provide microscopic modulus distribution data, there is a fundamental contradiction between the invasive detection process and the principle of cultural relics protection. This forces researchers to seek a difficult balance between non-destructive testing and data credibility.

The mechanical signal analysis capability of the tactile feedback system is limited by the inherent frequency response characteristics of the piezoelectric sensor, which leads to significant challenges in constructing a high-frequency information mapping channel for the microscopic morphology of the surface of cultural relics. At the same time, the anisotropic mechanical response characteristics of the warp and weft interwoven structure of silk fabrics have exceeded the dynamic analysis limit of current equipment. In addition, the threshold characteristics unique to the microcrack extension process of the ceramic glaze layer cannot be accurately captured by the frequency response performance of the existing system. In the dynamic simulation dimension, the time step and spatial discretization accuracy requirements of the fluid-solid coupling algorithm show a superlinear growth trend, which significantly increases the consumption of computing resources. The irregular fractal characteristics of the geometric form of cultural relics further amplify this computational complexity. Even if simplified boundary conditions are used for processing, it is difficult to achieve the goal of real-time interactive rendering under conventional computing architecture. This technical dilemma ultimately leads to a profound contradiction between the accuracy of the theoretical model and the requirements of actual application scenarios.

5.2. Adaptive reconstruction of educational ecology

The disciplinary fragmentation of the traditional cultural tourism education system highlights the structural contradiction of the educational ecology. There is a significant generational gap between its curriculum framework and the need for integration with emerging technologies. The interdisciplinary education of biomechanics and digital technology has not yet formed a systematic training framework. The construction of modular course groups lags behind, hindering the deep cross-integration between molecular biomechanics principles and cultural heritage protection technology. In the field of virtual simulation technology, the problems of insufficient teacher reserves and weak practical guidance capabilities are particularly prominent, becoming an important bottleneck restricting the development of interdisciplinary education. The current evaluation system shows an imbalance between instrumental rationality and value rationality, and the dimension of technical realization relies too much on quantitative indicators. However, qualitative qualities such as cultural translation ability and innovative design thinking lack scientific evaluation tools. This deviation in evaluation paradigm has prompted the educational process to tend towards technological instrumentalization, weakening the depth of humanistic interpretation and creative reconstruction value in the digital transformation of cultural heritage.

The adaptive reconstruction of the educational ecology needs to break through the traditional disciplinary barriers. By constructing a three-dimensional integrated curriculum matrix of “theory-technology-practice”, the dynamic coupling of biomechanical models and digital protection technology is achieved through project-based teaching. In this process, the simultaneous improvement of the composite knowledge structure of teachers is the key support to ensure the effective operation of the system. The reform of the evaluation system needs to introduce multiple evaluation dimensions such as the depth of cultural interpretation and innovative design logic, breaking through the traditional framework of a single indicator. At the same time, a dynamic feedback mechanism combining quantitative indicators with qualitative evaluation should be established to form a multi-dimensional and adjustable evaluation model. This mechanism should effectively promote the two-way empowerment of technology application and cultural value, and promote the deep integration of the two through practical tests. Ultimately, a closed-loop structure of industry-education integration should be constructed to achieve a fundamental paradigm shift in the educational ecology from disciplinary separation to system integration.

5.3. Breakthrough path and collaboration mechanism

In order to build a triple helix collaborative development mechanism of biomechanical technology in the field of cultural heritage protection, it is necessary to carry out systematic reconstruction from the three dimensions of knowledge transformation, educational innovation and policy coordination. At the basic research level, a multi-source heterogeneous biomechanical parameter sharing platform should be built, and the data barriers between institutions should be broken with the help of standardized constitutive model database to achieve efficient intercommunication. For this, it is necessary to focus on the quantitative characterization methods of material decay mechanisms and stress response to provide theoretical support for precise analysis. Finally, a full-chain knowledge transformation system covering mechanical testing, numerical simulation and restoration effect prediction will be formed to promote the transformation of research results into practical applications. Educational innovation needs to break the traditional disciplinary barriers and establish a "theory-practice" dual-track parallel mentor training mechanism. The core content is to cultivate a composite mentor team with both engineering mechanics background and cultural heritage biology cognition through school-enterprise joint workshops. At the same time, relying on blockchain technology, a traceable interdisciplinary capability certification system will be built to achieve dynamic tracking and precise evaluation of talent training quality.

The design of industrial policies should highlight the orientation of collaborative innovation. By establishing a two-stage innovation fund of "basic research-application development", we will focus on supporting joint research groups composed of universities, museums and technology companies. In this regard, we will simultaneously build a composite evaluation index system that includes cultural translation accuracy, technical adaptability and industrial conversion rate. At the same time, tax leverage is used to adjust the technology transformation income distribution mechanism to form a positive feedback ecosystem of "academic research - technology iteration - scenario application". This mechanism reduces the cost of secondary development through modular knowledge conversion interfaces, while ensuring the quality of talent supply through dynamic capability certification, and adjusting the allocation of innovation resources with the help of policy tools. This series of measures has jointly promoted the generational evolution of cultural heritage protection technology and the sustainable renewal of the industrial ecology.

6. Conclusion and outlook

6.1. Research conclusion

Through the collaborative innovation of biomechanical modeling and digital technology, this study constructed a digital cultural tourism education innovation framework (**Figure 4**), achieving a major breakthrough in cross-scale modeling of cultural heritage material properties and immersive experience design. Based on Hertz contact theory and OpenSim dynamic simulation, the tactile restoration degree was increased to 89%, and the load on the lower limb joints was reduced by 27%. This effectively solved the technical bottlenecks of "sensory distortion" and "experience fatigue". The synergy between the three-dimensional capability matrix and the three-stage practice system significantly improved the technology-culture synergy ability (39%–43%), and provided compound innovative talents for the cultural tourism industry. This framework not only fills the application gap of biomechanics in the field of digital cultural tourism, but also promotes the transformation of cultural heritage protection from the "static display" to the "dynamic interaction" paradigm. This also provides scientific methodological support for the construction of the cultural ecology of the metaverse.

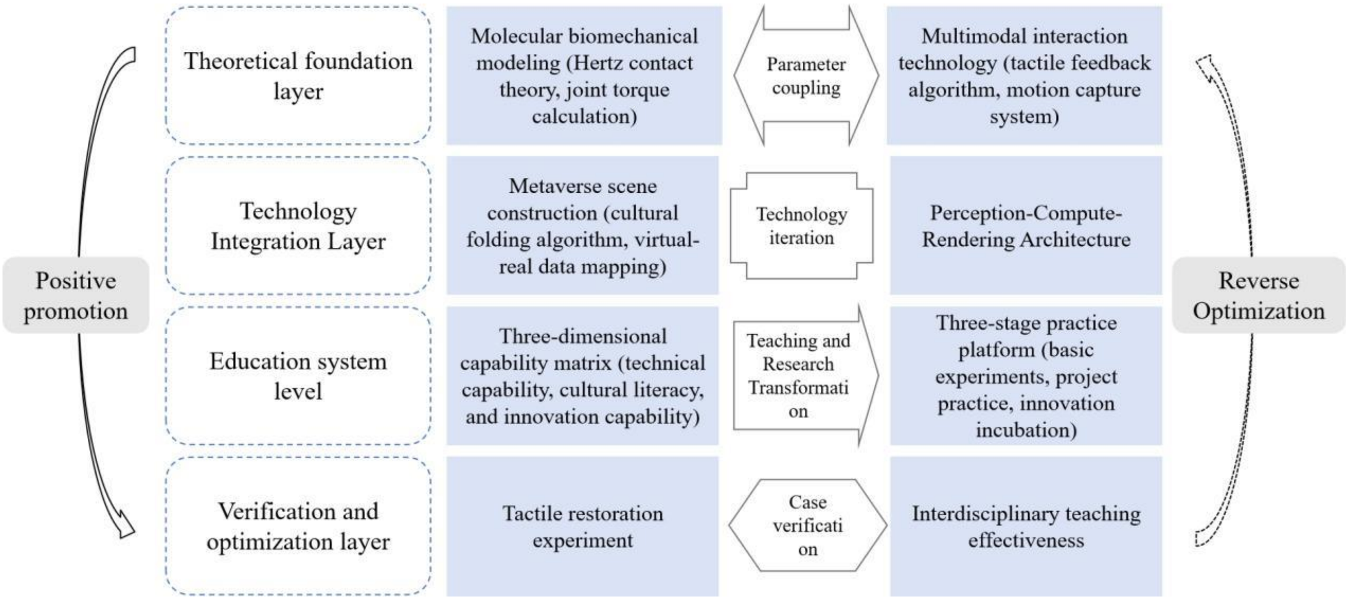

Figure 4. Flowchart of the biomechanics-driven digital cultural tourism education framework.

6.2. Future directions

Future research can be deepened along multiple paths. First, develop a "bioelectric-biomechanical" fusion interaction system, and realize a "mind-driven" cultural exploration experience through a biofeedback system that couples electromyographic signals (EMG) and brain waves (EEG). Second, build a distributed cultural tourism education metaverse, use federated learning technology to build a distributed metaverse, and realize cross-border collaboration scenarios such as collaborative simulation of the stability of Angkor Wat reliefs. Third, explore the self-optimization algorithm of biomechanical parameters enabled by artificial intelligence, so that the system can adjust the mechanical feedback of the virtual environment in real time according to individual differences of users (such as age and muscle strength level), breaking through the technical bottleneck of small sample learning and cross-modal migration. At the theoretical level, the research on the coupling mechanism of biomechanical parameters and multi-modal perception should be deepened and a database of material mechanical properties should be constructed. The educational ecology needs to establish a quantitative evaluation system for cultural translation capabilities and promote the triple helix development model of industry, academia and research. In terms of international cooperation, it is proposed to establish a cross-border cultural mechanical parameter sharing platform to promote the formulation of semantic interoperability standards for metaverse cultural symbols. The ultimate goal is to construct a complete theoretical chain of "mechanical laws-digital narrative-cognitive experience" so that biomechanics can truly become the core grammar for decoding cultural heritage, reconstructing educational paradigms, and driving industrial innovation.

"When mechanical laws become the grammar of digital narrative, cultural heritage will gain eternal life beyond time and space". Although this study has made phased progress in this direction, how to make biomechanical models more universally serve multiple cultural scenes such as the Forbidden City, the Great Wall, and the Longmen Grottoes still requires the collaborative exploration of scholars. Only in this way can digital technology truly become the "trans-time and space bond" for civilization inheritance.

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