人工智能动作捕捉赋能太极拳传播：中国菏泽地区的融合创新与路径

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摘要：研究目的：本研究立足于“健康中国 2035”“智能科技赋能传统体育”“人工智能+文化”三重政策驱动背景，针对菏泽地区太极拳“活态传承纵深性、地域技法独特性、群众基础广泛性”的结构性优势与“教学标准化缺失、师资结构性失衡、代际传承危机”的现实困境，提出以人工智能动作捕捉技术为核心驱动力，构建“科技赋能文化，数据驱动传承”的数字化传播新范式。研究旨在实现三大目标：1.技术适配性突破：针对菏泽特色技法（如“低架活步”空间轨迹、“缠丝劲”肌骨动力学），开发专用动作捕捉算法，解决通用技术对地域性非遗适配不足的问题；2.传播融合创新：构建“动作精度-文化语义”双轮驱动的标准化教学体系与文化转译机制，破解传统教学主观性强、抽象哲学概念难以量化表达的困境；3.路径创新验证：通过轻量化边缘部署（延迟 28±3ms）、文化语义转化机制（如“虚实→肘部抬高 3cm”），形成可复制的“人工智能+非物质文化遗产”活态传承技术链，服务于区域性非遗的科学化传承与普惠化传播。**研究方法：**本研究采用跨学科协同研究框架，整合计算机视觉、运动生物力学、非遗保护理论与体育教育学方法论，具体方法包括：1.实验研究法。高精度动作数据采集：使用 Xsens 惯性传感器（精度 0.1°）与 Mediapipe 计算机视觉框架，采集菏泽地区太极拳的标准动作数据，覆盖“野马分鬃”等核心招式的动态轨迹（采样频率 100Hz）；多模态算法开发：构建时空卷积神经网络（ST-CNN），融合视觉骨骼点数据与惯性传感器信息，针对“低架活步”开发空间轨迹特征提取算法（Z 轴位移误差<2cm），对“缠丝劲”建立肌骨动力学仿真模型（关节力矩解析精度达 0.1Nm）；轻量化系统部署：基于 MobileNetV2 的轻量化架构（3.4M 参数）与 Jetson Nano 边缘算力，通过 FP16 量化（JetPack + TensorRT）和选择性通道剪枝（压缩率 25%），在 300×300 分辨率下达成 28±3ms 延迟的实时视觉系统。迁移至 Jetson Orin Nano 后，结合 INT8 量化可实现<5ms 超低延迟。2.调查研究法。求调研：对菏泽基层拳会的 523 名练习者进行问卷与访谈，量化分析教学痛点（动作错误定型率>42%）与数字化学习偏好（VR 交互需求占比达 78%）；效果评估：在 3 个教学试点部署原型系统，通过五级评估量表（含动作准确性、文化语义理解度等维度）收集用户反馈，驱动系统迭代优化。3.案例研究法。聚焦菏泽陈氏太极拳

流派，深度解析“低架活步”桩功（高度较常规低 22.3±3.5cm）与“缠丝劲”发力特征（螺旋角 15°-25°），构建参数化风格保留策略，平衡地域特色与标准化需求。4.跨学科理论融合。融合菏泽“书画之乡”“戏曲之乡”“牡丹之都”的文化基因（如“水墨动画-招式演示”联动），引入非遗活态传承理论，设计“数据采集（动作库）→智能分析（算法）→文化传播（应用）”完整技术链；结合认知科学，开发文化语义转化机制：通过 NLP 技术将“虚实转换”等抽象概念映射为“肘关节抬升 3cm±0.5cm”等可量化指令。**研究结果：**1.技术性能突破。专用算法显著提升地域动作识别精度，“低架活步”桩高误差<1.2cm（较基线模型降低 76%），“缠丝劲”螺旋角解析误差<0.8°；轻量化系统实现 28±3ms 延迟响应，支持区域站点 10 路并发处理；构建首个专注菏泽太极拳流派的时序动作数据库（TH-TAIJI），包含 7 大非遗流派的 12,800 个动作序列。基于 ST-CGAN 生成对抗网络扩充数据规模至原始样本的 21 倍，所有数据提供三维关节姿态（17 关键点）及运动学特征标签，采样率 60Hz，平均序列长度 252 帧。2.传播效能提升。教学实验组动作标准化率提升至 89.7%（对照组：57.3%），错误动作定型率降至 11.2%（降幅>30%）；文化语义转化机制使抽象概念学习效率提升 2.4 倍（“虚实转换”掌握时间：23min vs 55min）；青少年参与比例从 15%增至 38%（VR 组留存率达 91%）。3.理论模型验证。“形意双轮驱动模型”通过结构方程验证（CFI=0.93）：动作精度（β=0.81）与文化语义传达（β=0.79）共同解释传播效能 82.3%变异；地域特色参数化方案平衡标准化与风格化：核心要领一致率>95%下，保留流派间肘关节角度差异（±5°-8°）。**研究结论：**1.技术-文化适配性路径：针对地域性非遗需开发“文化本体感知算法”，本研究证实：融合肌骨动力学（如缠丝劲角动量）与计算机视觉的多模态特征提取框架，可突破通用动作捕捉对非遗技法的表征瓶颈；2.双轮驱动传播范式有效性：“动作精度-文化语义”模型解决了技术应用与文化价值剥离的痛点，量化评估显示：文化语义转化机制使学员对太极拳哲学的理解深度提升 41.6%（p<0.001）；3.轻量化普惠部署可行性：边缘计算设备（Jetson Nano）在区域站点的成功部署（延迟 28±3ms），为破解师资区域失衡提供了关键技术基座，覆盖效率较传统面授提升 8 倍；4.跨学科方法论的创新性：构建的“计算机视觉+生物力学+非遗保护”融合框架，为传统体育数字化建立了可复用的理论工具包，其核心指标（如文化语义代理变量集）可迁移至其他非遗项目。本研究证实：以人工智能动作捕捉为核心的技术链，能够系统性解决地域性非遗传承中的“标准化缺失、师资失衡、代际危机”三大痛点，其“数据驱动传承、跨界融合创新、边缘普惠部署”的实施路径，为传统体育类非物质文化遗产的创造性转化与创新性发展提供可复制的“菏泽方案”。

关键词：动作捕捉；太极拳数字化；非遗活态传承；边缘计算

AI Motion Capture Empowers Tai Chi Dissemination: Integrated Innovation and Pathways in Heze, China

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Abstract: This study addresses critical challenges in preserving Heze's regionally distinctive Tai Chi—characterized by low-stance fluid steps and reeling silk force kinetics—amidst issues of instructional standardization, teacher shortages, and intergenerational gaps. Under China's "Healthy China 2035" and "AI + Culture" initiatives, we propose a digital transmission paradigm: "Technology Empowers Culture, Data Drives Transmission." An interdisciplinary methodology (computer vision, biomechanics, intangible cultural heritage (ICH) safeguarding) was employed: 1. Specialized Algorithms: A spatio-temporal CNN fused Xsens inertial sensors (0.1° precision) and MediaPipe vision data (100Hz) to capture Heze-specific movements. Achieved high accuracy: stance height error <1.2 cm (76% improvement), reeling force spiral angle error <0.8°;2. Lightweight System: Deployed on Jetson Nano edge devices via model quantization and pruning, enabling real-time feedback (28±3 ms latency) for 10 concurrent users;3. Dual-Drive Model: Integrated technical precision with cultural-semantic translation (e.g., mapping philosophical "substantial-insubstantial" to biomechanical "elbow elevation: 3 cm ±0.5 cm").4. TH-TAIJI Database: Compiled 12,800 sequences across 7 Heze lineages (60Hz), expanded 21× using generative adversarial networks. Results from 523 practitioners and 3 pilot sites demonstrated:1. Technical Efficacy: Stance recognition error reduced by 76%; real-time edge processing sustained 28±3 ms latency;2. Learning Outcomes: Standardized action rate rose to 89.7% (vs. 57.3% control); error persistence dropped >30%. Cultural-semantic mechanisms accelerated abstract concept mastery by 2.4× (e.g., 23 vs. 55 minutes for "substantial-insubstantial");3. Engagement: Youth participation increased from 15% to 38% (91% VR retention).4. Validated Model: Structural equation modeling confirmed the dual-drive framework (CFI=0.93) explains 82.3% of transmission efficacy (β_{Technical}=0.81, β_{Cultural}=0.79), preserving stylistic nuances (±5°–8° elbow variation) while maintaining >95% core consistency. Conclusions:1. Culture-aware multimodal algorithms overcome limitations of generic motion capture for ICH;2. The dual-drive model bridges technical precision and cultural essence, deepening philosophical understanding by 41.6% ($p<0.001$);3. Edge deployment enables

scalable, low-cost dissemination (8× coverage efficiency vs. traditional teaching);4. The interdisciplinary framework offers a replicable "Heze Solution" for sports ICH revitalization, aligning with global health and cultural sustainability goals. **Research Purpose:** This study, grounded in the tripartite policy-driven context of "Healthy China 2035," "Intelligent Technology Empowering Traditional Sports," and "AI + Culture," addresses the structural strengths of Tai Chi in the Heze region—namely, the "depth of living transmission, uniqueness of regional techniques, and extensive grassroots participation"—alongside its practical challenges: "lack of teaching standardization, structural imbalance in instructors, and crisis in intergenerational transmission." We propose Artificial Intelligence (AI) motion capture technology as the core driver for constructing a novel digital dissemination paradigm centered on "technology empowering culture, data driving transmission." The research aims to achieve three primary objectives: 1.Technological Adaptability Breakthrough: Develop specialized motion capture algorithms for Heze's characteristic techniques (e.g., spatial trajectories of "low-stance fluid stepping," musculoskeletal dynamics of "silk-reeling force"), addressing the insufficient adaptability of generic technologies to regional intangible cultural heritage (ICH).2.Dissemination Integration Innovation: Construct a standardized teaching system and cultural translation mechanism driven by the dual wheels of "movement precision" and "cultural semantics," overcoming the limitations of traditional teaching methods (subjectivity, difficulty in quantifying abstract philosophical concepts).3.Pathway Innovation Validation: Formulate a replicable technological chain for "AI + ICH" living transmission, featuring lightweight edge deployment (latency: 28±3ms) and cultural semantic conversion mechanisms (e.g., translating "xu-shi (void-solid)" to "elbow elevation of 3cm"), serving the scientific preservation and inclusive dissemination of regional ICH. **Research Methods:** Employing an interdisciplinary collaborative research framework integrating computer vision, sports biomechanics, ICH preservation theory, and physical education pedagogy, specific methods include: 1.Experimental Research: High-precision Motion Data Acquisition: Collected standard Tai Chi movement data in Heze using Xsens inertial sensors (accuracy: 0.1°) and the Mediapipe computer vision framework, covering dynamic trajectories of core movements like "Parting the Wild Horse's Mane" (sampling frequency: 100Hz). Multimodal Algorithm Development: Built a Spatio-Temporal Convolutional Neural Network (ST-CNN) fusing visual skeletal point data and inertial sensor information. Developed a spatial trajectory feature extraction algorithm for "low-stance fluid stepping" (Z-axis displacement error <2cm) and established a musculoskeletal dynamics simulation model for "silk-reeling

force" (joint torque resolution: 0.1Nm). Lightweight System Deployment: Implemented a real-time visual system using a MobileNetV2 lightweight architecture (3.4M parameters) and Jetson Nano edge computing. Achieved 28±3ms latency at 300×300 resolution via FP16 quantization (JetPack + TensorRT) and selective channel pruning (compression rate: 25%). Migration to Jetson Orin Nano with INT8 quantization enables ultra-low latency <5ms. 2.Survey Research: Needs Assessment: Conducted questionnaires and interviews with 523 practitioners from grassroots Heze boxing associations, quantitatively analyzing teaching pain points (incorrect movement habit formation rate >42%) and digital learning preferences (VR interaction demand: 78%).Effectiveness Evaluation: Deployed prototype systems in 3 teaching pilots; collected user feedback via a five-level assessment scale (covering movement accuracy, cultural semantic understanding, etc.) to drive iterative system optimization.3.Case Study: Focused on the Heze Chen-style Tai Chi school, deeply analyzing the characteristics of "low-stance fluid stepping" postures (height 22.3±3.5cm lower than standard) and "silk-reeling force" exertion (spiral angle: 15°-25°), constructing a parametric style retention strategy to balance regional distinctiveness and standardization needs.4.Interdisciplinary Theoretical Integration: Integrated Heze's cultural DNA ("Hometown of Calligraphy & Painting," "Hometown of Chinese Opera," "Peony Capital") – e.g., linking "ink-wash animation" with movement demonstrations – and ICH living transmission theory to design the complete technological chain: "Data Acquisition (movement library) → Intelligent Analysis (algorithms) → Cultural Dissemination (application)."Incorporated cognitive science to develop cultural semantic conversion mechanisms: Used NLP techniques to map abstract concepts like "xu-shi transition" into quantifiable instructions such as "elbow joint elevation of 3cm±0.5cm." **Research Results:** 1.Technological Performance Breakthroughs: Specialized algorithms significantly enhanced recognition accuracy for regional movements: "Low-stance fluid stepping" posture height error <1.2cm (76% reduction vs. baseline models); "Silk-reeling force" spiral angle resolution error <0.8°.Lightweight system achieved 28±3ms latency, supporting concurrent processing for 10 regional stations. Established the first temporal movement database (TH-TAIJI) focused on Heze Tai Chi schools, containing 12,800 movement sequences across 7 ICH lineages. Expanded data volume 21-fold using ST-CGAN generative adversarial networks. All data provides 3D joint poses (17 keypoints) and kinematic feature labels (sampling rate: 60Hz, average sequence length: 252 frames). 2. Dissemination Effectiveness Enhancement: Movement standardization rate in the experimental teaching group rose to 89.7% (control group: 57.3%); incorrect movement habit formation rate dropped to 11.2%

(>30% reduction). Cultural semantic conversion mechanisms improved abstract concept learning efficiency by 2.4 times (time to master "xu-shi transition": 23min vs 55min).Youth participation rate increased from 15% to 38% (VR group retention rate: 91%).3.Theoretical Model Validation: The "Form-Meaning Dual-Wheel Model" was validated via structural equation modeling (CFI=0.93): Movement precision (β=0.81) and cultural semantic communication (β=0.79) jointly explained 82.3% of the variance in dissemination effectiveness. Parametric regional style solutions balanced standardization and stylization: Achieved >95% consistency on core principles while preserving inter-school elbow joint angle differences (±5°-8°). **Research Conclusions:** 1. Technology-Culture Adaptability Pathway: Developing "cultural ontology-aware algorithms" is essential for regional ICH. This study confirms that a multimodal feature extraction framework combining musculoskeletal dynamics (e.g., silk-reeling force angular momentum) and computer vision can overcome the representational limitations of generic motion capture for ICH techniques. 2. Effectiveness of the Dual-Wheel Dissemination Paradigm: The "Movement Precision-Cultural Semantics" model addresses the pain point of divorcing technical application from cultural value. Quantitative assessment shows the cultural semantic conversion mechanism increased learners' depth of understanding of Tai Chi philosophy by 41.6% ($p<0.001$).3.Feasibility of Lightweight Inclusive Deployment: Successful deployment of edge computing devices (Jetson Nano) at regional stations (latency 28±3ms) provides a key technological foundation for alleviating instructor imbalance, increasing coverage efficiency 8-fold compared to traditional face-to-face teaching.4.Innovation in Interdisciplinary Methodology: The constructed "Computer Vision + Biomechanics + ICH Preservation" integrated framework establishes a reusable theoretical toolkit for traditional sports digitization. Its core metrics (e.g., cultural semantic proxy variable sets) are transferable to other ICH projects. **Research Recommendations:** To promote the sustainable development of the "AI + Traditional Sports" integration model, the following four-dimensional recommendations are proposed: Technology Deepening: Build a "Skeletal-Muscular-Biomechanical" triadic analysis model; integrate EMG signal capture to enhance resolution of complex force methods like "silk-reeling force" (sampling frequency ≥200Hz). Collaborate with the National Wushu Research Institute to formulate "Technical Standards for Digitizing Traditional Sports ICH," establishing standardized measurement systems for core movement parameters. Advocate for provincial cultural tourism cloud platforms to open movement database interfaces. Model Promotion: Implement phased regional pilots – Short-term: Establish an "AI Coach Station" network covering 87

boxing associations in Heze; Medium-term: Construct a digital Tai Chi transmission belt along the Yellow River Basin; Long-term: Advance the "Belt and Road" Wushu ICH Digital Corridor. Innovatively develop an "ICH Digital Passport" certification system and "Metaverse Martial Arts Hall," unlocking digital collectibles via movement challenges, utilizing blockchain for cross-spacetime master-disciple matching. Policy Safeguards: Establish provincial-level "AI + ICH Living Transmission" special funds, subsidizing ≥50% of village/town edge computing device deployment costs. Create a tripartite management mechanism (technology-culture-tourism-education) to integrate smart Tai Chi systems into Shandong Province's primary and secondary school physical education electives by 2026. Formulate "Ethical Guidelines for Traditional Sports Digitization," clarifying ownership principles (e.g., inheritors hold copyright of raw data; research institutions obtain usage rights). Talent Cultivation: Pilot "ICH Digitization" interdisciplinary programs in universities, implementing a dual-tutor system (AI experts + ICH inheritors). Establish a new professional certification system for "Traditional Skill Digital Translatologists," annually training 20 interdisciplinary talents proficient in both traditional techniques and AI application. This study demonstrates that a technology chain centered on AI motion capture can systematically address the three core pain points in regional ICH transmission – "lack of standardization, instructor imbalance, and intergenerational crisis." Its implementation path of "data-driven transmission, cross-boundary integrated innovation, and edge-based inclusive deployment" provides a replicable "Heze Model" for the creative transformation and innovative development of traditional sports intangible cultural heritage.

Keywords: Motion Capture; Tai Chi Digitization; Intangible Cultural Heritage (ICH) Living Transmission; Edge Computing