

Research Article

Strain-controlled reversible skyrmion evolution in van der Waals ferromagnet Fe_3GaTe_2 **Shuai Zhang^{1,#}, Shou-Zhe Dong^{2,#}, Zhao Zhang¹, Hou-Bing Huang^{2,3}, Cheng-Chao Hu^{1,3}**¹School of Materials Science and Engineering, Liaocheng University, Liaocheng 252000, Shandong, China.²School of Interdisciplinary Science, Beijing Institute of Technology, Beijing 100081, China.³Aerospace and Informatics Domain, Beijing Institute of Technology, Zhuhai 519088, Guangdong China.

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Reversible, field-free manipulation of magnetic skyrmions is desirable for low-power topological spintronic devices. Here, phase-field simulations demonstrate field-free strain control of a skyrmion in a nanoisland of the two-dimensional van der Waals (vdW) ferromagnet Fe_3GaTe_2 . The applied strain continuously tunes the skyrmion size and morphology. With increasing strain, the skyrmion evolves from a circular state through elliptical deformation and progressive shrinkage to eventual annihilation. The



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skyrmion radius initially decreases from 63 nm at zero strain to approximately 22 nm at 0.45% strain. A distinct shrinkage regime occurs over 0.45-0.70% strain, during which the radius continuously decreases to 10 nm. The skyrmion recovers its initial configuration upon unloading throughout this range, whereas irreversible annihilation occurs at strains of 0.75% and above. Energy analysis shows that the strain-induced elastic energy shifts the balance among magnetic anisotropy, exchange, and Dzyaloshinskii-Moriya interaction (DMI) energies. The resulting compression of the domain wall region progressively weakens DMI-mediated chiral stabilization and promotes skyrmion collapse. These results clarify the mechanism of strain-induced topological transitions in two-dimensional vdW ferromagnets and provide design guidance for field-free, low-power, programmable topological spintronic devices.

Keywords: Fe_3GaTe_2 , magnetic skyrmion, strain engineering, phase-field simulation

INTRODUCTION

Two-dimensional van der Waals (vdW) ferromagnets provide an attractive platform for spintronic applications because of their reduced dimensionality, tunable magnetic properties, and compatibility with layered heterostructures^[1-4]. Magnetic skyrmions, which represent a class of spin textures with nontrivial topological properties, combine nanoscale dimensions with topological protection and therefore exhibit great potential for applications in high-density information storage and logic devices^[5-8]. Compared with conventional metallic thin films, vdW ferromagnets provide a more versatile platform for realizing low-dimensional and controllable skyrmion states. Fe_3GaTe_2 is a recently discovered two-dimensional vdW ferromagnet that possesses a Curie temperature of approximately 350 K and strong perpendicular magnetic anisotropy, making it a promising material system for investigating topological spin textures near room temperature^[9-13]. In particular, in the ultrathin limit, the competition among exchange interaction, Dzyaloshinskii-Moriya interaction (DMI) and magnetoelastic coupling becomes increasingly pronounced in Fe_3GaTe_2 , rendering it an ideal model system for exploring strain-mediated control of skyrmion behavior^[12-15].

The formation and stability of skyrmions primarily depend on the energetic competition among exchange interaction, perpendicular magnetic anisotropy, and the DMI^[16,17]. External magnetic fields, spin-polarized currents, and spin-orbit torques are widely employed to manipulate skyrmion motion and induce topological transitions^[5,18-23]. However, these approaches are often accompanied by considerable energy consumption or complex device architectures, which limit their applications in low-power and adaptive spintronic devices. Mechanical strain couples directly to lattice degrees of freedom and is particularly effective in two-dimensional materials^[24-28]. Owing to the low in-plane elastic modulus of vdW materials, strain significantly modifies magnetic anisotropy and magnetoelastic energy, thereby offering an alternative strategy for magnetic structure manipulation that differs fundamentally from current- and field-driven approaches. Previous studies have demonstrated that strain can induce magnetic-domain reconstruction and even trigger the emergence or annihilation of skyrmion states^[25-27]. Nevertheless, existing investigations mainly focus on the phase transition associated with skyrmion formation, while the strain-driven evolution of skyrmion morphology, size variation, and reversibility window insufficiently understood.

In this work, phase-field simulations are employed to investigate the morphology evolution and stability of skyrmions in a Fe₃GaTe₂ nanoisland under uniaxial strain and in the absence of an external magnetic field. By systematically varying the strain magnitude, the strain-dependent behavior of skyrmions is explored. The results show that skyrmions undergo a sequential evolution from elliptical deformation to progressive size reduction and eventual annihilation as the applied strain increases, with a well-defined critical strain threshold identified for the topological state transition. Within a moderate strain range, the skyrmion size exhibits reversibility upon strain release. These findings demonstrate that strain serves as an efficient and reversible mechanical approach for manipulating topological spin textures in two-dimensional ferromagnetic systems.

MATERIALS AND METHODS

A phase-field model is employed to simulate the magnetic structures in a two-dimensional vdW ferromagnet Fe_3GaTe_2 nanoisland. The local magnetization vector $\mathbf{M}$ (m_1, m_2, m_3) serves as the main order parameter and its spatial distribution characterizes the magnetic-domain microstructure^[29-31]. The temporal evolution of the magnetization is governed by the Landau-Lifshitz-Gilbert (LLG) equation^[29]:

$$(1 + \alpha^2) \frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\gamma_0 \alpha}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}}) \quad (1)$$

where M_s is the saturation magnetization, α and γ_0 are the damping constant and the gyromagnetic ratio, respectively. $\mathbf{H}_{\text{eff}}$ is the effective magnetic field, which can be given as^[29]:

$$\mathbf{H}_{\text{eff}} = \frac{-1}{\mu_0 M_s} \frac{\delta E_{\text{tot}}}{\delta \mathbf{m}} \quad (2)$$

where μ_0 and E_{tot} denote vacuum permeability and the total free energy, respectively. The total free energy consists of several contributions^[29]:

$$E_{\text{tot}} = E_{\text{stray}} + E_{\text{anis}} + E_{\text{exch}} + E_{\text{dmi}} + E_{\text{elas}} \quad (3)$$

where E_{stray} , E_{anis} , E_{exch} , E_{dmi} , E_{elas} are the stray field energy, magnetocrystalline anisotropy energy, exchange energy, DMI energy, and elastic energy, respectively. The magnetocrystalline anisotropy energy can be written as^[32]:

$$E_{\text{anis}} = \iiint_v \left[K_1 (1 - m_3^2) + K_2 (1 - m_3^2)^2 \right] dV \quad (4)$$

where K_1 and K_2 are the anisotropy constants. Considering that Fe_3GaTe_2 is a layered vdW ferromagnet, only the interfacial DMI is included in the present work^[22]. The corresponding energy density is expressed as^[32]:

$$E_{dmi} = \iiint_V D_{interface} (m_3 \nabla \cdot \mathbf{m} - \mathbf{m} \cdot \nabla m_3) dV \quad (5)$$

where $D_{interface}$ is the interfacial DMI constant. The elastic energy arising from local deformation is expressed as^[29,33]:

$$E_{elas} = \iiint_V \frac{1}{2} c_{ijkl} e_{ij} e_{kl} dV = \int_V \frac{1}{2} c_{ijkl} (\varepsilon_{ij} - \varepsilon_{ij}^0) (\varepsilon_{kl} - \varepsilon_{kl}^0) dV \quad (6)$$

where c_{ijkl} is the elastic stiffness tensor, e_{ij} is the elastic strain, ε_{ij} is the total strain, and ε_{ij}^0 is the stress-free strain.

The simulations are performed using a ferromagnetic/ferroelectric (FM/FE) multiferroic heterostructure nanoisland model. As illustrated in Figure 1A, the system consists of a ferromagnetic nanoisland and a ferroelectric layer. An in-plane strain is generated in the ferroelectric layer by an applied voltage and is subsequently transferred to the ferromagnetic layer through interfacial magnetoelastic coupling, thereby enabling indirect electric-field control of the magnetic configuration^[25]. The island size is $256 \times 256 \times 17 \text{ nm}^3$, and the number of cells is $128 \times 128 \times 17$. Specifically, we set the 17-layer grids, of which the bottom 11 layers of grids represent the elastically stiff ferroelectric layer, the middle 2 layers represent the magnetic island and the top 4 layers represent the space on top of the magnet. The diameter of the magnetic island is 200 nm. The magnetic parameters used in the simulations are as follows^[15,34]: $M_s = 2.4 \times 10^5 \text{ A/m}$, $A_{ex} = 5 \times 10^{-12} \text{ J/m}$, $\alpha = 0.04$, $K_1 = 8 \times 10^4 \text{ J/m}^3$, $K_2 = 0 \text{ J/m}^3$, $D_{interface} = 0.8 \times 10^{-3} \text{ J/m}^2$. From our prior first-principles calculations^[28], the Young's modulus and Poisson's ratio are $E = 32 \text{ GPa}$ and $\nu = 0.458$, yielding elastic constants of $C_{11} = 141.6 \text{ GPa}$, $C_{12} = 119.7 \text{ GPa}$, and $C_{44} = 10.97 \text{ GPa}$. Combined with the procedure of Zhuang *et al.*^[4], the magnetostriction coefficient is estimated to be $\lambda_s = -517 \text{ ppm}$.

RESULTS AND DISCUSSION

We first investigate the evolution of skyrmions under different magnitudes of uniaxial tensile strain (ε_{yy}). To generate the initial skyrmion state, the magnetization was initialized uniformly along $[00\bar{1}]$ and a perpendicular magnetic field of 80 kA/m was applied for 0.5 ns. After field removal, the system relaxed to a stable isolated Néel-type skyrmion^[23,27]. After the initial skyrmion state is established, all subsequent strain modulation is carried out without applying any external magnetic field. In the absence of external strain, a stable skyrmion configuration with a radius of 63 nm forms in the nanoisland, as shown in Figure 1B. The skyrmion radius is defined as the radius of the $m_z = 0$ contour. This magnetic state results from the energy balance among exchange interaction, perpendicular magnetic anisotropy, demagnetization energy, and the DMI. In a finite-size nanoisland, skyrmion formation depends not only on the intrinsic material parameters but also on geometric confinement. The island boundary enhances the edge demagnetization field, while spin canting near the boundary partially reduces the exchange energy. These effects facilitate skyrmion stabilization in confined nanostructures compared with infinite films^[32]. As shown in Figure 1C, the skyrmion undergoes a pronounced strain-dependent evolution with increasing ε_{yy} . The initially circular skyrmion first becomes elongated along the strain direction, resulting in an elliptical shape. Upon further increasing the strain, the skyrmion continuously shrinks and eventually annihilates, leaving a single-domain state at sufficiently large strain.

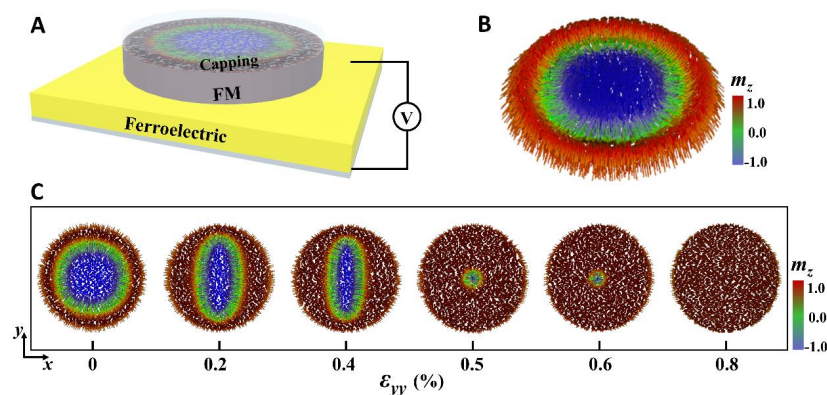


Figure 1. (A) Schematic illustration of the FM/FE multiferroic heterostructure nanoisland used in the phase-field simulations; (B) Stable Néel-type skyrmion

configuration in the Fe₃GaTe₂ nanoisland; (C) Evolution of the skyrmion spin texture under different levels of uniaxial tensile strain.

Magnetoelastic coupling serves as the primary mechanism through which strain modifies the skyrmion structure. At relatively small strains ($\varepsilon_{yy} < 0.5\%$), tensile strain in Fe₃GaTe₂, which possesses a negative magnetostriction coefficient, drives the magnetization to preferentially align along the strain direction in order to reduce the magnetoelastic energy. This preferred orientation breaks the in-plane rotational symmetry and produces an anisotropic energy distribution along the x- and y-directions. Consequently, the initially circular skyrmion gradually evolves into an elliptical configuration. This behavior is physically consistent with the strain-driven evolution of Néel-type skyrmions reported by Dong *et al.*^[32]. When ε_{yy} reaches 0.5% and 0.6%, the skyrmion shrinks substantially to 17 nm and 13 nm, respectively. When the magnetoelastic energy becomes a significant contributor to the total free energy of the system, the skyrmion domain wall width decreases, leading to a continuous reduction in the skyrmion radius. According to the scaling relation of skyrmion size^[35,36]:

$$R \propto \pi D \sqrt{\frac{A}{16AK_{eff}^2 - \pi^2 D^2 K_{eff}}} \quad (7)$$

where D is the DMI strength and K_{eff} is the effective magnetic anisotropy. Through magnetoelastic coupling, the applied strain increases K_{eff} , thereby driving a reduction in the skyrmion radius. Although strain-dependent DMI is not considered in the present model, this mechanism adequately accounts for the monotonic decrease in skyrmion size with increasing strain. At $\varepsilon_{yy} = 0.8\%$, the energy compensation provided by the topological spin texture becomes insufficient to sustain the complete rotational configuration. Consequently, the system evolves toward the energetically favorable single-domain state. As a result, the skyrmion is annihilated.

To elucidate the physical origin of the strain-driven skyrmion evolution, the temporal evolution of the energy contributions is analyzed in Figure 2. Before strain application

($t = 0-5$ ns), all energy terms remain nearly constant, indicating a stable balance among the exchange, DMI, magnetocrystalline anisotropy, and magnetostatic interactions that stabilizes the isolated skyrmion. When a tensile strain of $\varepsilon_{yy} = 0.5\%$ is applied at $t = 5$ ns, the elastic energy increases rapidly and becomes the dominant strain-induced contribution, accounting for approximately 52% of the total energy at equilibrium, as shown in the inset of Figure 2. This additional contribution disrupts the initial energy balance and drives the system toward a new constrained equilibrium. Skyrmion contraction reduces both the domain wall area and the number of canted spins, resulting in an approximately 75% reduction in the magnetocrystalline anisotropy energy. Meanwhile, the magnitude of the DMI energy decreases by approximately 64%, indicating a progressive weakening of the chiral stabilization associated with the compressed domain wall structure. In contrast, the exchange energy increases by approximately 14% because of the enhanced magnetization gradients within the contracted spin texture, whereas the magnetostatic energy changes only slightly. These energy variations indicate that strain compresses the skyrmion by modifying the competition among the elastic, anisotropy, exchange, and DMI contributions, ultimately weakening the chiral stabilization required to maintain its topological integrity.

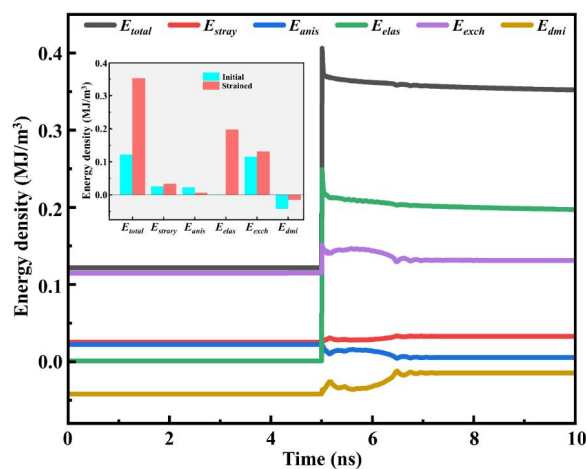


Figure 2. Time evolution of the elastic, anisotropy, exchange, DMI, and magnetostatic energies after the application of a uniaxial tensile strain of $\varepsilon_{yy} = 0.5\%$ at $t = 5$ ns. The

inset compares the equilibrium energy densities before strain application and after relaxation under the applied strain.

To further investigate the strain range for skyrmion shrinkage and its reversibility, the evolution of skyrmions during the loading and unloading processes under different strain levels is examined. As shown in Figure 3A, under moderate strain ($0.4\% < \varepsilon_{yy} \leq 0.7\%$), the skyrmion undergoes deformation, substantial shrinkage, or even approaches annihilation during loading. Nevertheless, the compressed core region retains a continuous chiral spin texture, allowing the skyrmion to recover its initial configuration after strain release. This behavior demonstrates excellent reversibility. However, the recovery depends critically on the strain magnitude. When the applied strain exceeds a critical value ($\varepsilon_{yy} \geq 0.75\%$), the topological core disappears completely. Re-nucleation of the skyrmion then requires overcoming a substantial energy barrier. Consequently, the skyrmion fails to recover after strain release and the system remains in a single-domain state. In this regime, the system crosses the topological stability barrier and undergoes an irreversible topological transition. The strain dependence of the skyrmion radius is quantitatively summarized in Figure 3B, which identifies four characteristic regimes of skyrmion evolution. In the low-strain regime, the initially circular skyrmion undergoes pronounced elliptical deformation, accompanied by a rapid reduction in its characteristic size from approximately 63 nm in the unstrained state to about 22 nm at $\varepsilon_{yy} = 0.45\%$. When the strain increases from 0.45% to 0.7%, the skyrmion enters a continuous shrinkage regime. Its radius decreases to approximately 17 nm at $\varepsilon_{yy} = 0.5\%$, 13 nm at $\varepsilon_{yy} = 0.6\%$, and 10 nm at $\varepsilon_{yy} = 0.7\%$. A narrow critical-transition region appears between 0.7% and 0.75%, in which the residual skyrmion core becomes increasingly unstable. At $\varepsilon_{yy} = 0.75\%$, the radius abruptly decreases to zero, indicating complete annihilation of the reversed core and the formation of a uniform single-domain state. Therefore, the radius-strain relationship quantitatively confirms that the interval between 0.7% and 0.75% separates reversible skyrmion modulation from irreversible topological annihilation.

For practical device applications, single-cycle reversibility alone is insufficient. Reliable output under repeated operation is of greater importance^[37,38]. Figure 3C presents the magnetic response during repeated strain loading-unloading cycles. The skyrmion consistently recovers its initial configuration throughout multiple cycles without noticeable distortion or random domain formation. This demonstrates robust cyclic stability at $\epsilon_{yy} = 0.5\%$. The observed cyclic stability arises from the combined effects of skyrmion topological protection and geometric confinement provided by the nanoisland.

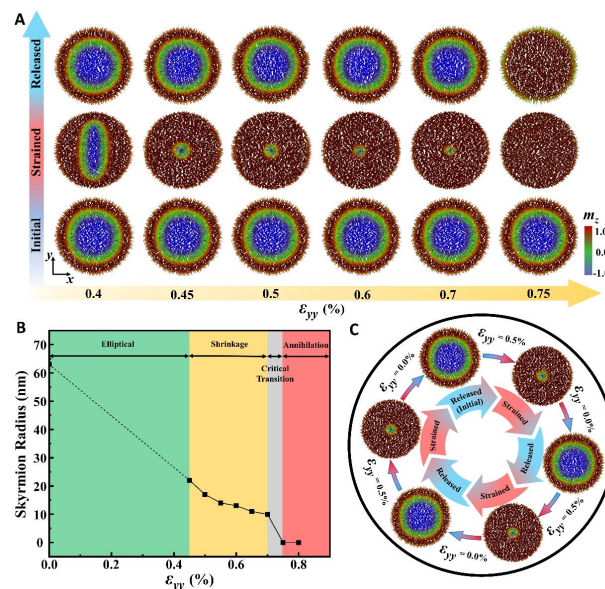


Figure 3. (A) Evolution of the skyrmion during strain loading and unloading under different tensile strain amplitudes; (B) Variation of the skyrmion radius as a function of the applied uniaxial tensile strain (ϵ_{yy}). Four characteristic strain regimes are identified: elliptical, shrinkage, critical transition, and annihilation; (C) Cyclic response of the skyrmion under repeated strain loading-unloading operations ($\epsilon_{yy} = 0.5\%$).

Skyrmion shrinkage or annihilation directly modulates the net out-of-plane magnetization of the nanoisland. As the applied strain increases, the skyrmion radius decreases, resulting in a monotonic increase in the spatially averaged m_z . This variation in m_z can be electrically detected through the anomalous Hall effect (AHE) or tunnel magnetoresistance (TMR), enabling the evolution of the skyrmion size to be monitored

without the need for an external magnetic field^[39-41]. Figure 4A shows the correlation between the strain response of skyrmions and the corresponding device output. The unstrained skyrmion state is defined as the output signal ‘0’, while the compressed skyrmion state is defined as the output signal ‘1’. Under periodic modulation of ε_{yy} , the skyrmion reversibly evolves among the stable, compressed, and recovered states, accompanied by synchronous variations in the output signal. This behavior enables information encoding based on strain-controlled topological magnetic states. The FM/FE nanodot crossbar architecture illustrated in Figure 4B provides a possible device architecture for strain-programmable skyrmion devices. By selectively addressing individual nanodots through word and bit lines, localized strain can be generated to regulate the skyrmion size and consequently modulate the output signal^[37,38]. Combined with a simple crossbar-array architecture and the intrinsically low-power nature of strain control, this platform offers a promising route toward low-power, high-density topological memory and neuromorphic computing architectures. Beyond the reversible strain regime, when the applied strain exceeds the critical threshold, the skyrmion state transforms into a uniform single-domain state and remains unchanged after strain removal. This irreversible strain-induced skyrmion annihilation enables permanent information encoding through a strain-triggered topological-state transition, providing the physical basis for the concept of one-time programmable (OTP) magnetic memory.

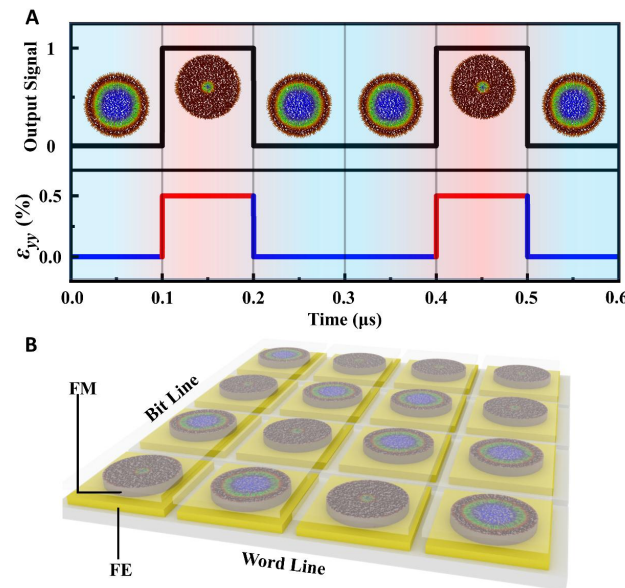


Figure 4. (A) Evolution of the skyrmion radius and the corresponding output signal during strain loading and unloading; (B) Conceptual FM/FE nanodot architecture for strain-mediated control of skyrmion states.

CONCLUSION

In summary, phase-field simulations show that uniaxial tensile strain can manipulate a skyrmion in a Fe_3GaTe_2 nanoisland without an external magnetic field. With increasing strain, the skyrmion evolves from elliptical deformation through progressive shrinkage to annihilation. A pronounced, reversible shrinkage regime spans 0.45-0.70% strain, during which the skyrmion radius continuously decreases from approximately 22 to 10 nm and the initial configuration is recovered upon unloading. At applied strains of 0.75% and above, however, the skyrmion annihilates irreversibly, and the system remains in a single-domain state after unloading. Energy analysis indicates that strain-induced elastic energy redistributes the exchange, effective anisotropy, and DMI energy contributions. The resulting reduction of the domain-wall region contracts the skyrmion and progressively weakens DMI-mediated chiral stabilization. Mechanical strain therefore enables both reversible skyrmion-size modulation and irreversible topological switching, providing a potential route to low-power, programmable spintronic devices based on two-dimensional vdW magnets.

DECLARATIONS

Authors' contributions

Conception and design of the study: Hu CC, Zhang Z, Zhang S;

Data analysis and interpretation: Zhang S, Hu CC, Dong SZ;

Manuscript writing and revising: Zhang S, Zhang Z, Dong SZ;

Simulation guide: Huang HB, Hu CC;

Supervision: Hu CC, Zhang Z.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI and AI-assisted tools statement

Not applicable.

Financial support and sponsorship

This work was financially supported by the National Natural Science Foundation of China (No. 52301088). We would also like to express our gratitude to the Liaocheng “Vice President of Science and Technology” Collaborative Innovation Project (No. 2024XT05).

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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