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Article

Teaching strategies for resolving gastrointestinal function from the perspective of cell biomechanics

Bo Qian[1], Zihao Qin[1], Shuo Liu[1], Fuzhen Wan[1], Rui Yu[2,*]

[1] Department of General Surgery, The Second Affiliated Hospital of Anhui Medical University, Hefei 230601, China
[2] Department of Infectious Diseases, The First Affiliated Hospital of Anhui Medical University, Hefei 230022, China
*** Corresponding author:** Rui Yu, yurui20141018@126.com

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Abstract: Traditional gastrointestinal function teaching focuses on biochemical and physiological regulation, but fails to explore the effects of mechanical forces on gastrointestinal cell behavior and function, resulting in students' one-sided understanding of gastrointestinal function. This paper proposes a new teaching strategy by combining cell biomechanics with teaching to help students master the gastrointestinal function mechanism more comprehensively. First, the membrane elasticity of gastrointestinal smooth muscle cells is measured. The elastic modulus is calculated by combining the Hertz model and the applied force is controlled to avoid cell membrane damage. Elasticity change data is obtained. Then, a flexible substrate is used to apply stretching and low frequency to simulate the mechanical force of cells during peristalsis and monitor the fluctuation of calcium ion concentration. Then, the distribution of intercellular cadherin is analyzed, and mechanical force is used to accelerate the permeability of gap junctions and the expression of Connexin43 to promote signal transmission. Finally, a teaching experiment based on cell biomechanics is designed, covering cell culture, mechanical stimulation, quantitative analysis and molecular biology verification, to help students understand how mechanical forces affect gastrointestinal cell behavior and function. The results show that before and after the application of the cell biomechanics teaching strategy, the students' test scores increase by 16%, and the experimental results are good. Applying biomechanical factors into teaching by combining teaching strategies with cell biomechanics has a positive effect on medical education.

Keywords: gastrointestinal function; cell biomechanics; mechanical force; elastic modulus; signal transmission

1. Introduction

Gastrointestinal function is vital to human health, especially in digestion and absorption. It also involves multiple physiological functions such as immune response and endocrine balance [1,2]. Therefore, in-depth exploration of the operating principles of gastrointestinal function is of great significance to medical education and clinical practice. However, traditional medical education focuses on the explanation of gastrointestinal physiology and biochemical mechanisms, but pays insufficient attention to how the mechanical microenvironment affects cell function and activity [3,4]. The field of cell biomechanics focuses on exploring the response mechanism of cells under mechanical stress, and its importance has become increasingly prominent in multiple branches of biology in recent years. Studies have shown that differences in mechanical environment can significantly change cell morphology, proliferation rate, migration pattern and differentiation pathway [5,6]. For example, smooth muscle cells in the gastrointestinal tract respond to mechanical

stretch and compression signals, which can affect the metabolic activity and functional regulation of cells [7,8]. In the current teaching of gastrointestinal function, the emphasis on biomechanics is obviously insufficient, resulting in students' one-sided understanding of gastrointestinal function and their inability to deeply grasp the important role of mechanical force in cell behavior [9,10]. Solving this problem can not only improve students' learning effects, but also lay a more solid foundation for future medical research and clinical applications.

In order to improve the existing teaching strategies of gastrointestinal function, this paper applies the perspective of cell biomechanics to analyze gastrointestinal function and guide students to understand and experimentally analyze gastrointestinal function. This paper adopts the methods of cell biomechanics analysis, experimental design and curriculum integration to deeply explore the behavior of cells under different mechanical environments in the gastrointestinal tract [11,12]. Through theoretical analysis and experimental observation of the behavior of cells under mechanical force, combined with students' teaching feedback, the regulatory effect of mechanical force on gastrointestinal cell function is explored [13,14]. Specifically, the study designs a series of experimental courses to allow students to personally participate in cell mechanics experiments and observe the influence of mechanical force on cell behavior through practical operations. In addition, the course content also includes the basic principles and applications of cell biomechanics to improve students' theoretical knowledge and practical ability.

The research results show that the teaching strategy combined with cell biomechanics not only significantly improves students' understanding of gastrointestinal function, but also enhances their ability in practical operations. Students show a deeper understanding of the mechanical signal response of gastrointestinal cells, which provides a theoretical basis and practical guidance for future improvements in medical education. Through this study, this paper hopes to promote the reform of medical education, so that it can more comprehensively and systematically cover the importance of biomechanics in clinical practice, and lay a solid foundation for cultivating higher-level medical talents.

2. Related work

Many scholars have conducted extensive research on the regulatory mechanisms of gastrointestinal function, mainly focusing on biochemical signals and neural regulation.

Mercado-Perez [15] described the mechanical factors related to normal function, as well as the molecules, cells and circuits involved in gastrointestinal mechanosensing, and finally outlined the important unanswered questions in gastrointestinal mechanosensing. Li [16] summarized the typical characteristics of human stomach and small intestinal motility and the biomechanical and fluid dynamic events related to intestinal motility. He discussed the simulation of gastrointestinal motility in existing dynamic in vitro models from an engineering perspective, and divided them into hydraulic, piston/probe drive, roller drive, pneumatic and other systems. Feng [17] applied biomechanics and mechanical drive to gastrointestinal visceral pain and reviewed the research on mechanosensitive ion

channels in colorectal afferent neurons. Taghadosi [18] proposed an electromechanical model of human gastric wall smooth muscle contraction under physiological conditions. In this model, the electromechanical contraction of smooth muscle is due to electrophysiological slow waves (due to ionic interactions between cells and the extracellular environment and neighboring cells) distributed on 240 cells and 548 links, explaining the biomechanical regulation mechanism of smooth muscle. The results of McGinn [19] pointed out a simple mechanism, that is, mechanical changes experienced at the whole tissue level are combined with changes perceived at the cellular level to control the fate of epithelial cells.

However, most existing studies have ignored the key role of biomechanical signals in gastrointestinal function, especially the behavioral regulation mechanism of cells under mechanical force has not been fully explored [20,21]. Therefore, current research is somewhat one-sided in understanding the mechanism of gastrointestinal diseases. In recent years, cell biomechanics has gradually been applied to the study of various physiological and pathological processes. Studies have demonstrated the effect of mechanical force on bone cell growth and the regulatory effect of mechanical stress on cardiomyocyte function [22,23]. These research results reveal that mechanical force has a great impact on cell function, opening up a new perspective for complex physiological mechanisms in medicine [24–26]. Current research methods are mostly limited to specific categories and have not yet been fully integrated into the analysis of gastrointestinal cells and functions [27–29]. In view of this, this paper advocates a teaching strategy that integrates cell biomechanics and gastrointestinal function research, using a combination of experimental and theoretical methods to enable students to fully grasp the key role of mechanical force in the regulation of gastrointestinal function.

3. Cell mechanical properties

3.1. Measurement of cell membrane elasticity

Membrane elasticity refers to the ability of a cell membrane to deform under external forces, reflecting the rigidity and flexibility of the membrane. It is usually evaluated by measuring the response of the cell membrane to external forces. This paper evaluates the elastic parameters of cell membranes under external mechanical forces, and uses atomic force microscopy (AFM) technology to measure the membrane elasticity of gastrointestinal smooth muscle cells. Under simulated gastrointestinal physiological conditions, cultured smooth muscle cells are fixed on an AFM carrier. A small force is applied by the probe to record the cell membrane deformation, and the elastic modulus is calculated using the Hertz model. This method overcomes the limitations of traditional tensile tests in quantifying cell microscopic elasticity and provides high-precision mechanical parameters [30,31]. In the experiment, the force application range is precisely controlled to avoid cell membrane damage, and the elastic changes of the cell membrane under normal and abnormal pressures are obtained, providing an experimental basis for teaching.

Figure 1 shows the force-displacement curves of three smooth muscle cells under normal and stress conditions to assess the mechanical properties of cells under different physiological states. Each sub-figure shows the force data of cell 1, cell 2,

and cell 3, respectively, where the red scattered points represent the force under normal conditions and the green scattered points represent the force under stress conditions. The maximum force reached by cell 1 under normal conditions as the displacement increased is 0.05 μN, while it increases to 0.08 μN under stress conditions, showing a significant effect of stress on the mechanical properties of cells. The force values of cells 2 and 3 show similar trends, increasing to 0.09 μN and 0.1 μN under stress conditions, respectively. The fitting curve of the Hertz model further verifies the enhanced mechanical response of cells under stress conditions. The data shows that cells show higher elastic modulus and mechanical adaptability under stress, which provides an important reference for studying the function of smooth muscle cells under pathological conditions.

Figure 1. Force-displacement curves of three smooth muscle cells under normal and stress conditions.

3.2. Cytoskeleton structure

In order to further explore the effect of mechanical force on cell morphology and movement, the composition of the cytoskeleton is studied and analyzed. The cytoskeleton is composed of microtubules, microfilaments and intermediate filaments, which play a role in structural support and force transmission when the cell is subjected to mechanical stress. In this paper, immunofluorescence staining and confocal microscopy techniques are used to analyze the distribution and reconstruction of the cytoskeleton. In the experiment, smooth muscle cells are stained with specific antibodies to mark tubulin, actin and intermediate filaments, and then confocal microscopy is used to capture images of the cytoskeleton under different mechanical stresses. Image analysis software is used to quantify the changes in the density, direction and relative length of the cytoskeleton fibers to evaluate their response under different mechanical force conditions.

Figure 2 shows the cytoskeleton images of four different positions of smooth muscle cells under a microscope after specific staining of the cytoskeleton of smooth muscle cells, with a scale of 50 microns. **Figure 2** shows the dynamic response of the cytoskeleton and its role in cell shape maintenance and deformation, solving the limitation of using electron microscopes to obtain dynamic information of living cells. The experimental results show that during normal gastrointestinal peristalsis,

the skeletal structure of smooth muscle cells is normally densely arranged. Students can understand and analyze cell mechanical forces by observing cell behavior.

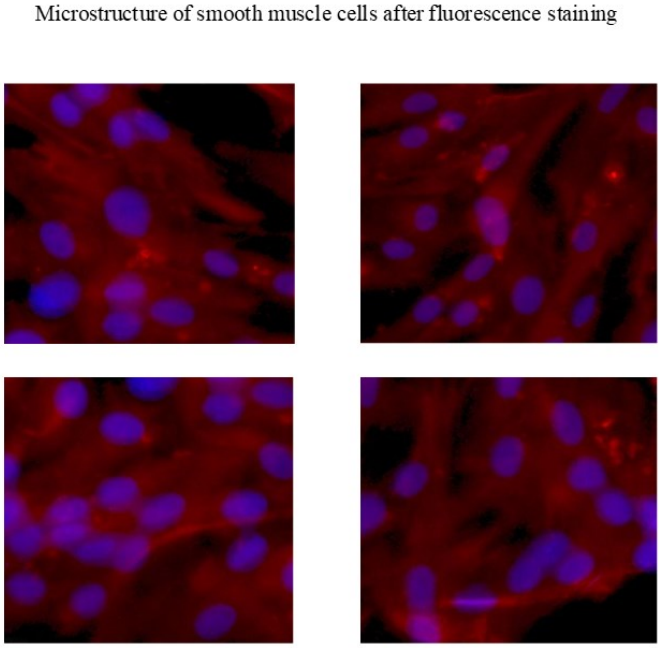

Figure 2. Fluorescence stained cytoskeleton.

3.3. Cell shape and movement

A microfluidic equipment is used to simulate the fluid environment in the gastrointestinal tract. Cells are fixed in specific fluid channels, allowing different mechanical stresses to be applied from the outside to observe the shape changes and movement trajectories of cells in dynamic force fields.

Cultured smooth muscle cells are inoculated on microfluidic chips one after another. The flow speed and flow rate of the channel are used to simulate the various mechanical environments during human gastrointestinal peristalsis. Then, the imaging system is used to record the changes in cell morphology under various mechanical stresses and the movement path of the cells in real-time during the experiment [32,33]. Parameters such as cell movement speed, shape variation rate, and shape recovery rate are extracted, as shown in **Table 1**:

Table 1. Parameters of smooth muscle cells under mechanical stress conditions.

Mechanical Stress (Pa)	Cell Movement Speed (μm/min)	Shape Variability (%)	Shape Recovery Rate (S^{-1})	*p*-value (Speed)	*p*-value (Shape Variability)	*p*-value (Recovery Rate)
0	5.2	3.1	0.15	0.032	0.054	0.028
1	8.4	4.5	0.22	0.014	0.039	0.017
2	12.3	6.8	0.3	0.009	0.025	0.013
3	10.1	5.4	0.25	0.021	0.045	0.035
4	7.6	4	0.18	0.027	0.037	0.062
5	15	8.2	0.35	0.002	0.001	0.004
6	14.2	7.5	0.33	0.008	0.023	0.016

As shown in **Table 1**, with the increase of mechanical stress, the cell movement speed increases significantly between 0 Pa and 6 Pa, from 5.2 μm/min to a maximum of 15.0 μm/min, indicating that cells become more active under higher mechanical stress, which may be related to the enhanced responsiveness of cells to external forces. At the same time, the shape variation rate also increases from 3.1% to a maximum of 8.2%, indicating that under the action of mechanical force, the cell shape changes more significantly, reflecting the plasticity and adaptability of cells in adapting to the fluid environment. The shape recovery rate data shows that after the application of mechanical stress, the cells are able to recover their original shape at a faster rate, from 0.15 S^{-1} to 0.35 S^{-1}, which further demonstrates the biomechanical properties and self-repair ability of cells in dynamic force fields. The p values of all indicators are less than 0.05, indicating that the changes in cell behavior under different mechanical stress conditions are statistically significant. The smaller the p value, the less likely the difference between the data is due to chance, reflecting the high reliability of the impact of mechanical stress on cell biomechanical properties. For example, when 1 Pa mechanical stress is applied, the p-value of the cell movement speed is 0.014, indicating that the cell movement speed changes significantly under this condition.

Students can intuitively understand the impact of mechanical forces in the gastrointestinal tract on cell movement and morphology. Experimental observations show that cells show different morphological changes and movement patterns under different fluid stresses: cells stretch under low stress and contract and accelerate under high stress.

3.4. Gastrointestinal mechanical environment simulation

Based on the above experiments, this paper uses finite element modeling (FEM) to simulate and analyze the mechanical environment of the gastrointestinal tract. By constructing a cell mechanical model and embedding it into the finite element model of the gastrointestinal wall, combined with the cell elastic modulus and skeleton structure response obtained in the experiment, the peristaltic movement of different parts of the gastrointestinal tract under normal physiology is simulated. The model calculates the stress distribution of cells in different regions and its impact on morphological changes, and verifies the accuracy of the model by comparing with experimental data. FEM involves complex mathematical equations to describe the mechanical behavior of materials and the response of cells in a mechanical environment [34,35]. The following are equations related to this study, covering the calculation of elastic theory, stress distribution, displacement field and cell morphological changes. In elastic materials, the linear stress-strain relationship can be described by Hooke's law, as shown in Equation (1):

$$\sigma = E \cdot \epsilon \tag{1}$$

Among them, σ is stress (Pa); E is elastic modulus (Pa); ϵ is strain. In three-dimensional finite element analysis, the stress state of cells can be expressed by Equation (2):

$$\sigma_1 = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{pmatrix} \tag{2}$$

In Equation (2), σ_1 is the stress tensor; σ_{xx}, σ_{yy} and σ_{zz} are the principal stress components; σ_{xy}, σ_{xz}, and σ_{yz} are the shear stress components. The displacement of cells in the force field can be described by the relationship between the equilibrium equation and the displacement field. According to the equilibrium equation, the basic equation of the displacement field is:

$$F = \int_V \sigma \cdot n \, dV \tag{3}$$

In Equation (3), F is the external force acting on the unit volume; n is the surface normal vector; V is the cell volume. The shape change of cells under mechanical force can be expressed by the following deformation rate equation:

$$\frac{du}{dt} = \nabla u + u \cdot \nabla u \tag{4}$$

In Equation (4), $\frac{du}{dt}$ is the deformation rate per unit time; ∇ is the gradient operator; u is the displacement vector. Combining the four equations to study the behavior of gastrointestinal cells in a mechanical environment provides quantitative analysis.

4. Discussion of mechanical signals

4.1. Cell stretching experiment

First, a cell stretching experiment is used to simulate the mechanical stress encountered by gastrointestinal smooth muscle cells during peristalsis. In order to achieve precise stretching, this paper adopts a flexible substrate stretching system, cultures smooth muscle cells on an elastic film, and simulates the mechanical stretching effect produced by gastrointestinal peristalsis by regulating the magnitude and period of tension. The experimental process is as follows: gastrointestinal smooth muscle cells are inoculated in a culture dish covered with an elastic substrate, and the stretching experiment is started after the cells have grown adherently for 24 hours and entered a stable state. The stretching equipment applies periodic tension to the substrate. The stretching amplitude is set to 10% and the frequency is 1Hz to simulate the normal physiological state of gastrointestinal peristalsis. When comparing the calcium ion concentration between the mechanical stretching group and the control group, the experimental conditions were strictly controlled and consistent. The temperature in the cell culture incubator was stabilized at 37 ℃, the humidity was maintained above 95%, and light was avoided to simulate the physiological environment in vivo. The culture medium was DMEM containing fetal bovine serum and growth factors, the pH value was between 7.2–7.4, and the automatic adjustment system ensured a stable environment. The operators were professionally trained and strictly followed the aseptic operation specifications to ensure the accuracy of the experimental results. The experiment combines calcium ion fluorescence staining with high-resolution imaging technology to observe the

calcium ion fluctuations of smooth muscle cells under stretching conditions in real-time, and the changes in calcium ion concentration directly map the contractile activity of the cells. The monitoring results show that periodic stretching triggers calcium ion influx and enhances the contractile response of smooth muscle cells. By recording the amplitude and frequency of calcium ion concentration fluctuations, this paper further quantifies the effect of mechanical stretching on the improvement of cell contractility.

To ensure the reliability of the results, the stretched group is compared with the control group without mechanical stretching to observe the contraction efficiency of cells under different mechanical stresses. The data shows that under continuous cyclic stretching, the frequency of calcium ion concentration fluctuations in smooth muscle cells is significantly higher than that in the control group, and the intensity of cell contraction is significantly enhanced.

Figure 3 shows the dynamics of calcium ion concentrations in gastrointestinal smooth muscle cells at different positions under control and stretch conditions. At position 1, the calcium ion concentration in the control group is maintained at 1.0 μM, fluctuating by about 0.03 μM; the calcium ion concentration in the stretched group increases to 1.2 μM, and the fluctuation increases to 0.05 μM, highlighting the enhancing effect of stretching on cell contraction. Compared with the control group (1.05 μM), the concentration of the stretched group at position 2 increases to 1.15 μM, with a fluctuation of 0.06 μM, showing its sensitivity to stretching. The calcium ion concentration in the stretched group at position 3 increases from 1.0 μM in the control group to 1.15 μM, with a fluctuation of 0.05 μM, further confirming that stretching activates contraction signals. The calcium ion concentration in the control group at position 4 is higher (1.1 μM), while that in the stretched group reaches 1.2 μM, with a fluctuation of 0.07 μM, and the response is more significant. Comprehensive analysis shows that stretching significantly increases the calcium ion concentration and fluctuation of smooth muscle cells, indicating that periodic stretching regulates cell contraction through calcium signals, providing data support for understanding the effects of the mechanical environment on gastrointestinal function.

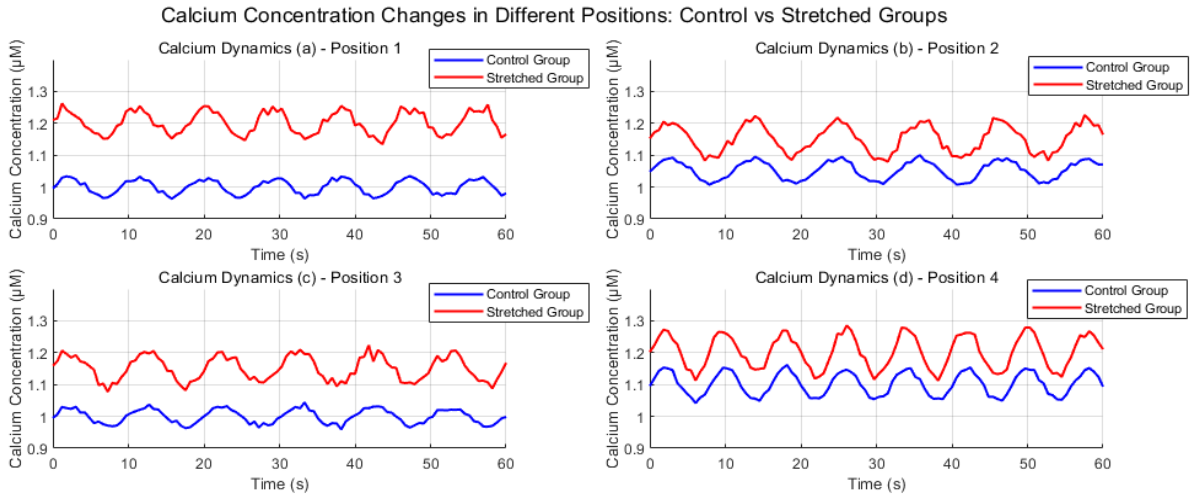

Figure 3. Changes in calcium ion concentrations at four positions of gastrointestinal smooth muscle cells.

In order to explore the effect of compression on the relaxation function of smooth muscle cells, a cell compression experiment is designed to simulate the compression force on the cells in the wall when food passes through the gastrointestinal tract. A microcolumn compression equipment is used to precisely control the compression stress, and the morphological changes of the cells under compression are observed under a microscope. Two compression intensities are set in the experiment: low compression (1 kPa) and high compression (5 kPa), simulating mild and strong compression reactions, respectively. Each compression cycle lasts for 5 s, with an interval of 10 s, repeating 10 cycles. The changes of cells under compression are recorded by real-time live cell imaging technology, and the rearrangement is observed by fluorescent labeling technology of cytoskeletal proteins. The experimental results show that low compression causes slight relaxation, while high compression causes significant relaxation accompanied by rearrangement of the cytoskeleton.

4.2. Association between mechanical force and signaling pathways

In order to further explore the association between mechanical force and cell signaling pathways, this study uses protein blotting and immunoprecipitation techniques to analyze the activation of related signaling pathways in gastrointestinal smooth muscle cells by stretching and compression, especially the regulatory effects of RhoA/ROCK and calcium ion signaling pathways [36,37].

After the stretching and compression experiments, cell samples are collected, and total intracellular proteins are extracted. The expression levels and phosphorylation states of RhoA (Ras Homolog Gene Family, Member A), ROCK (Rho-associated protein kinase), MLC (Myosin light chain), and CaM (Calmodulin) and CaMKII (Calmodulin-dependent protein kinase II) in the calcium ion signaling pathway are detected by WesternBlot. The results show that the stretching force significantly activates the RhoA/ROCK signaling pathway, promotes the phosphorylation of myosin light chain, and thus enhances the contractile function of the cells; the compression force promotes cell relaxation by inhibiting the pathway.

Table 2. Changes in the expression and phosphorylation levels of RhoA, ROCK, MLC and CaMKII under different experimental conditions.

Experimental Condition	RhoA Expression (fold change)	ROCK Expression (fold change)	MLC Phosphorylation (fold change)	CaMKII Phosphorylation (fold change)
Control Group	1	1	1	1
Stretched Group	2.3	2.1	2.5	2.2
Compression Group	0.7	0.8	0.6	0.9
Control Group (Repeat)	1	1	1	1
Stretched Group (Repeat)	2.4	2	2.6	2.1
Compression Group (Repeat)	0.8	0.7	0.7	0.8

Table 2 shows the changes in the expression and phosphorylation state of RhoA/ROCK pathway and calcium signaling-related proteins under different

experimental conditions. Under stretching treatment, the expression levels of RhoA and ROCK jump to 2.3 and 2.1 times of the baseline value, respectively, while the compression treatment causes them to decrease to 0.7 and 0.8 times, respectively, indicating that stretching activates the RhoA/ROCK pathway, and compression inhibits it. In addition, the phosphorylation ratio of myosin light chain (MLC) in the stretched group increases to 2.5 times, indicating a significant enhancement of the contractile potential of smooth muscle cells; on the contrary, the phosphorylation level of MLC in the compression group decreases to 0.6 times, and the contractile response is significantly inhibited. On the other hand, the phosphorylation state of CaMKII in the stretched group increases to 2.2 times, reflecting the activation of the calcium signaling pathway, while it slightly decreases to 0.9 times in the compression group.

To further explore the effects of stretching and compression on the interaction between signaling pathways, immunoprecipitation experiments are also performed. The results show that under the action of stretching force, the interaction between RhoA and CaM is significantly enhanced, while under the action of compression force, it is significantly weakened. These findings strongly prove that stretching strengthens the contractile function of smooth muscle cells by positively regulating the RhoA/ROCK pathway and calcium signaling pathway, while compression has the opposite effect and weakens the contractile efficiency of cells. The study of signaling pathways provides practical materials for teaching, helping students to deeply understand the complex interaction between mechanical force and signaling pathways.

5. Intercellular interaction mechanism

5.1. Measurement of intercellular adhesion junctions

In order to analyze the role of cell adhesion junctions in mechanical signal transmission, immunofluorescence staining and laser confocal microscopy are first selected to mark and observe the distribution of cell cadherin.

Gastrointestinal smooth muscle cells were seeded in a culture dish, and after the cells reached confluence, they were fluorescently labeled using cadherin-specific antibodies. The distribution of cadherin at cell boundaries was analyzed by laser confocal microscopy. The experiment set up a mechanical stimulation group and a control group. The mechanical stimulation was applied through a flexible base stretching system to simulate the tension generated by gastrointestinal peristalsis. In order to ensure the accuracy and reproducibility of experimental results, gastrointestinal smooth muscle cells need to be seeded on a specific matrix in a culture dish, and cultured using standardized culture media under appropriate conditions such as 37 ℃ and 5% CO_2. Ensure cells maintain normal physiological status and reach appropriate density in a controlled environment. After the cell culture reaches an appropriate density, mechanical stimulation experiments are performed. In addition, the stretching speed was precisely controlled through the flexible substrate stretching system, and the experiment was set with a frequency of 1 Hz and a stretching amplitude of 10% to simulate the normal physiological state of gastrointestinal peristalsis. The intensity of cadherin fluorescence signal was

quantified by image processing software, and the results showed that the distribution of intercellular cadherin significantly increased under the action of mechanical force, suggesting that mechanical stress promotes the enhancement of intercellular adherens connections. This result shows that cell adhesion molecules coordinate the joint contraction and relaxation of smooth muscle cells in mechanical signal transmission, thereby ensuring the coordinated operation of the overall function of the gastrointestinal tract.

Figure 4 (control group) shows that the signal intensity of intercellular cadherin is relatively low when no mechanical force is applied, with an average intensity of about 0.156, reflecting that the adhesion connection between cells is not tight enough, affecting the signal transmission and coordinated contraction function between cells. **Figure 4** (mechanical force stimulation group) shows that after mechanical stretching, the signal intensity of cadherin increases significantly, and the average intensity increases to about 0.705, indicating that mechanical stress significantly promotes the enhancement of intercellular adhesion connection, improves the mechanical coupling between cells, and thus enhances the contractile function of smooth muscle cells. This result verifies the key role of mechanical force in promoting the expression and function of intercellular adhesion molecules, provides an important basis for in-depth understanding of the mechanical signal transmission mechanism of the gastrointestinal tract under physiological conditions, and also emphasizes the importance of intercellular connection in the coordination of gastrointestinal function.

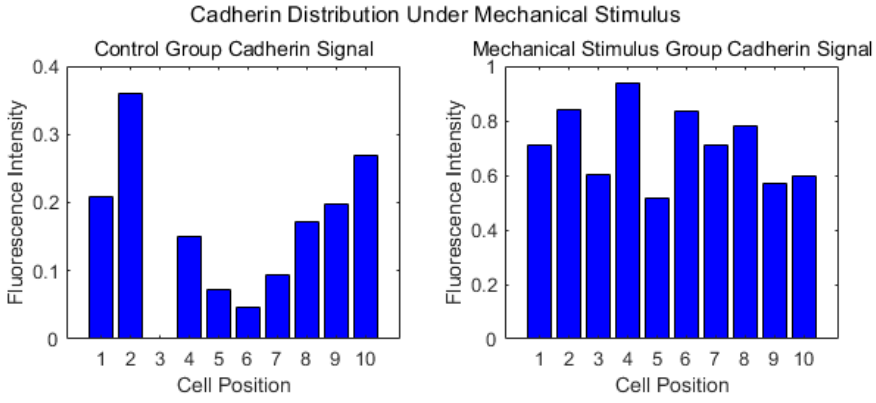

Figure 4. Fluorescence signal intensity of intercellular cadherin in gastrointestinal smooth muscle cells under different mechanical force conditions.

5.2. Intercellular gap junction

In order to further explore the mechanism of direct intercellular signal transmission, this study focuses on the role of connexin in intercellular mechanical signal transmission. The regulation of mechanical force on gap junction function is analyzed by combining dye transfer experiment with electrophysiological recording technology.

In the dye transfer experiment, gastrointestinal smooth muscle cells use gap junctions to achieve the communication of ions and small molecules. Fluorescently labeled calcium ion indicator (Fluo-4AM) is injected into the cells, and the

propagation speed and range of the fluorescent signal are monitored in real-time using a high-resolution fluorescence microscope [38]. The experiment sets up a mechanical force stimulation group and a control group, by applying a periodic stretching force that simulates gastrointestinal peristalsis. The results show that mechanical force stimulation significantly accelerates the transmission speed of fluorescent dye through gap junctions, indicating that mechanical force enhances the permeability of gap junctions. At the same time, the expression of Connexin43 in the mechanical force stimulation group is significantly upregulated, further confirming that mechanical stress activates the function of gap junctions and promotes the rapid transmission of intercellular signals. This mechanism is crucial for the coordinated response and overall functional coordination of gastrointestinal cells under mechanical force. This study provides experimental evidence of intercellular signaling for teaching, filling the gap in the understanding of intercellular interactions in traditional teaching.

5.3. Relationship between intercellular mechanical signals and overall function

In order to clarify how intercellular mechanical signals affect the overall function of the gastrointestinal tract, a computational model of gastrointestinal smooth muscle cells is established to simulate the effect of intercellular mechanical force transmission on the overall peristalsis of the intestine. The model is based on the cell mechanical data obtained from the above experiments, and the behavior of cell groups under different mechanical environments is simulated by finite element analysis (FEA).

Combining the data of optical tweezers experiments and gap junction and adhesion junction experiments, a multi-unit mechanical model of gastrointestinal smooth muscle cells is established. Different mechanical force fields (such as stretching and compression) are set in the model, and intercellular connections are simulated through elastic connectors.

Figure 5 depicts the effect of changes in cell connection strength on mechanical signal transmission efficiency. Both the horizontal axis (X-axis) and the vertical axis (Y-axis) represent the range of connection strength, from 0 (representing no connection state) to 1 (indicating full connection). The depth of color reflects the change in signal strength. The darker the red tone, the higher the transmission efficiency. The analysis reveals that with the increase in cell connection strength, the signal strength increases significantly, especially after the connection strength exceeds 0.7, the signal strength gradually approaches 0.6. This phenomenon shows that high-strength cell connection promotes signal transmission, further confirming the core role of mechanical signals in cell interaction. There is a positive correlation between cell connection strength and signal transmission efficiency. This model provides intuitive materials for teaching that combine theory with experimental results, which helps students to deeply understand the regulatory mechanism of cell interaction on gastrointestinal function, and effectively makes up for the lack of explanation of the connection between overall function and cell level in traditional teaching.

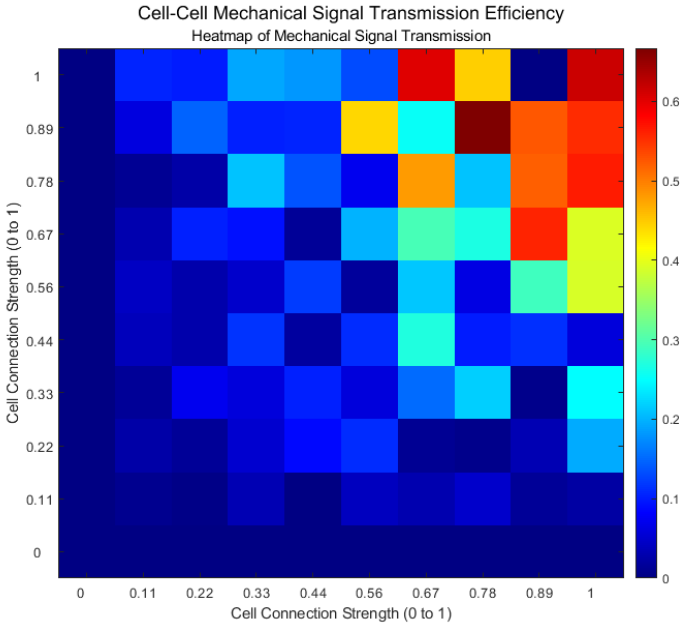

Figure 5. Changes in mechanical signal transmission efficiency under different cell connection strengths.

6. Teaching experiment design

The experimental design combines cell culture, mechanical stimulation, and observation and analysis, striving to make up for the neglect of biomechanical factors in traditional teaching and enhance students' comprehensive understanding of gastrointestinal function.

6.1. Cell culture preparation

First, gastrointestinal smooth muscle cells are cultured on a specific matrix to ensure that the cells maintain a normal physiological state under a controlled environment. Standardized culture mediums (such as DMEM culture medium containing fetal bovine serum and essential growth factors) are used, and the culture conditions are maintained at 37 ℃ and 5% CO_2. The replacement of culture medium and cell passaging operations strictly follow the aseptic operation standards. Students need to master basic cell culture skills during the experiment, including cell plating, passaging, and cell density detection. An inverted microscope is used to regularly observe the cells in culture to ensure that the cell morphology conforms to the characteristics of smooth muscle cells (such as spindle-shaped morphology and good adhesion).

Through the actual operation of cell culture, students can personally experience the control of cell growth conditions and changes in cell morphology, laying the foundation for subsequent mechanical mechanics experiments. At the same time, students need to understand the relationship between culture medium, temperature and cell state, which are all prerequisites for the success of cell mechanics experiments.

6.2. Mechanical stimulation experiment

After the cell culture reaches an appropriate density, a mechanical stimulation experiment is conducted. This experiment uses a flexible substrate cell stretching equipment to simulate the effect of mechanical force in the gastrointestinal tract. In the experiment, the cells are cultured on a flexible elastic substrate, and periodic mechanical stress is applied by setting the stretching frequency and amplitude (such as 1 Hz frequency and 10% stretching amplitude) for 6 hours to observe the cell response. The cell stretching system is used to precisely control the mechanical stress of smooth muscle cells. The experiment sets up a control group (cells not subjected to mechanical stimulation) and an experimental group (cells subjected to mechanical stimulation) to ensure that the conditions of the two groups are consistent, with the only difference being the effect of mechanical force. Students need to learn how to operate the stretching equipment and set relevant parameters to ensure that the experimental conditions are precisely controllable. Finally, an inverted microscope is used to observe and record the changes in cell morphology in real-time. This part of the experiment allows students to observe the flattening of cells after stretching and the rearrangement of the cytoskeleton through the changes in cell morphology, helping them understand how mechanical forces affect cell function through the cytoskeleton.

6.3. Quantitative analysis of cell mechanical behavior

To further quantitatively analyze the response of cells under mechanical stimulation, students need to conduct quantitative analysis of experimental data. Cell morphology analysis software (such as ImageJ) is used in the experiment to measure changes in parameters such as cell area, length, and width. The cell morphology data before and after mechanical stimulation are statistically compared to analyze the effect of mechanical stress on cell morphology. After the experiment, cell images are taken with a microscope, and cell morphology is quantitatively analyzed using ImageJ software. Students need to conduct statistical analysis of cell morphology changes in the experimental and control groups. Specific indicators include cell area, cell circumference, cytoskeleton fiber distribution, etc., to quantitatively assess the effect of mechanical force on cell morphological remodeling.

Table 3. Effects of mechanical stimulation on gastrointestinal smooth muscle cells.

Experimental Group	Cell Area (μm^2)	Cell Perimeter (μm)	YAP Expression (Relative Units)	p38MAPK Expression (Relative Units)	Cytoskeleton Fluorescence Intensity (Relative Units)	Cell Adhesion Strength (kPa)
Control Group	800 ± 50	100 ± 5	1.0 ± 0.1	1.0 ± 0.05	1.0 ± 0.1	2.5 ± 0.3
Experimental Group (Mechanical Stimulation 1)	950 ± 60	110 ± 6	1.5 ± 0.1	1.5 ± 0.1	1.5 ± 0.2	3.0 ± 0.2
Experimental Group (Mechanical Stimulation 2)	1100 ± 70	120 ± 7	1.8 ± 0.1	1.8 ± 0.1	1.8 ± 0.3	3.5 ± 0.1
Experimental Group (Mechanical Stimulation 3)	1300 ± 80	130 ± 8	2.0 ± 0.1	2.0 ± 0.1	2.1 ± 0.2	4.0 ± 0.2

Table 3 shows the effects of mechanical stimulation on gastrointestinal smooth muscle cells, which are specifically reflected by quantitative analysis of cell area, perimeter, expression of signaling pathway proteins YAP (Yes-Associated Protein) and p38MAPK, cytoskeleton fluorescence intensity, and cell adhesion strength. In the control group, the cell area and perimeter are 800 μm^2 and 100 μm, respectively; the expression levels of YAP and p38MAPK are both 1.0 (relative unit); the cytoskeleton fluorescence intensity and cell adhesion strength are 1.0 and 2.5 kPa, respectively, showing the basic characteristics of cells without mechanical stimulation. In the experimental group, after mechanical stimulation of different intensities, the cell area and perimeter increase significantly; especially in the third group, the cell area reaches 1300 μm^2 and the perimeter is 130 μm, indicating that mechanical force causes significant changes in cell morphology. At the same time, the expression levels of YAP and p38MAPK rise to 2.0, respectively, showing the strong activation of intracellular signaling pathways by mechanical stimulation. In addition, the fluorescence intensity of the cytoskeleton also increases to 2.1, indicating the reorganization and enhancement of the cytoskeleton, and the cell adhesion strength increases to 4.0 kPa, indicating that the adhesion and stability of the cells under mechanical stimulation are enhanced.

7. Indicators for assessing teaching effectiveness

7.1. Assessment of theoretical understanding ability

The assessment of theoretical understanding ability aims to test students' theoretical mastery of the relationship between cell biomechanics and gastrointestinal function, especially how mechanical force affects the behavior and function of gastrointestinal smooth muscle cells. Theoretical tests are conducted before and after the experiment, including relevant knowledge such as cell membrane elasticity, the composition and function of the cytoskeleton, and the biomechanical properties of gastrointestinal smooth muscle cells. The theoretical test uses standardized test questions, covering fill-in-the-blank, multiple-choice, short answer and discussion questions, to ensure that the test questions can fully cover the relevant theoretical knowledge points. Through theoretical tests, students' mastery of the theoretical knowledge of cell biomechanics and gastrointestinal function can be directly quantified, thereby assessing whether the teaching strategy has effectively improved students' theoretical understanding ability.

Figure 6 shows the changes in theoretical understanding ability of 30 students before and after the application of the cell biomechanics teaching strategy, and compares the performance of each student before and after the test. The blue line in **Figure 6** represents the score before the test, and the orange line represents the score after the test. It can be observed that before the test, most students' scores are concentrated around 60 points, with large fluctuations in scores, and the scores of some students are even lower than 40 points, indicating that students' traditional understanding of gastrointestinal function is relatively limited. However, after the application of the cell biomechanics teaching method, the average score of students after the test improves significantly, and most students' scores increase by about 10 points. Some students reach more than 80 points after the test, and the average score

increases by about 9.5 points, an increase of nearly 16%. The data changes reflect that the new teaching strategy effectively improves students' theoretical grasp of gastrointestinal function, especially the effect of mechanical force on the behavior of smooth muscle cells, and the effectiveness of the teaching strategy is verified by the difference in grades.

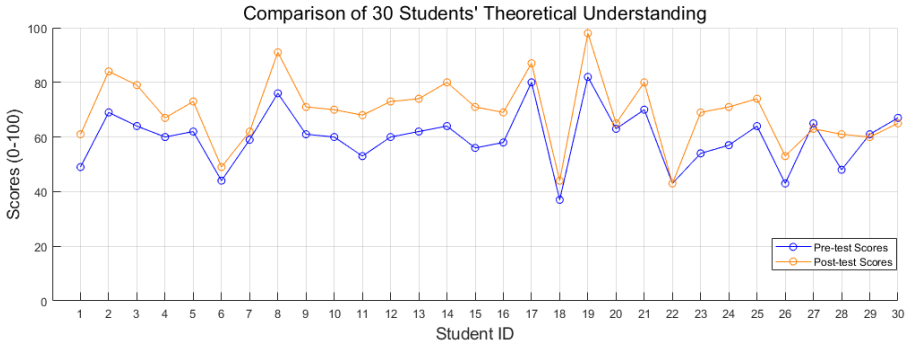

Figure 6. Changes in theoretical understanding ability.

7.2. Experimental operation ability assessment

The experimental operation ability assessment focuses on examining the students' skill level in actual experimental operation, including the accuracy and proficiency of key steps such as cell culture, operation of mechanical stimulation equipment, and cell observation and recording. The settings of the cell culture incubator include a constant temperature of 37 °C, a high humidity of more than 95%, and a light-proof environment to support the normal growth and metabolism of cells. The incubator is equipped with a temperature and humidity sensor to monitor and adjust the temperature and humidity in real time. The culture medium is usually DMEM containing fetal bovine serum and growth factors, and the pH value of the culture medium is monitored by a pH meter (usually maintained at 7.2–7.4). The control system automatically adjusts the temperature and humidity, and adjusts the pH value by adding buffers or replacing the culture medium when necessary. The experimental conditions are strictly controlled, and the operators are required to undergo professional training to ensure sterile operation and avoid contamination. In the experimental operation phase, students need to complete the cell culture and mechanical stimulation experiments independently, and the teacher records and scores each student's operation process through on-site observation and scoring sheets. The scoring sheet includes multiple dimensions, such as aseptic operation specifications for cell culture, setting and use of cell stretching equipment, and accuracy of cell morphology observation under a microscope.

By quantitatively scoring the operation process, it is possible to assess whether the teaching strategy has effectively improved students' experimental operation skills. This real-time operation assessment can ensure that the teaching strategy not only imparts theoretical knowledge, but also transforms theory into practical skills, helping students master the necessary operation skills in future scientific research and clinical practice.

Figure 7 shows the performance of 10 students of different levels in the experimental operation ability assessment of this class, including three assessment

dimensions: aseptic operation, equipment operation, and cell observation. In terms of aseptic operation, students 4 and 9 score the highest, reaching 9 points, showing their excellent experimental skills, while student 5 scores only 5 points, indicating that there is a lot of room for improvement in aseptic operation specifications. In terms of equipment operation, students 1 and 4 score 9 points, with high practical operation ability, while student 8 scores the lowest, only 5 points, indicating that the student may face challenges in using the equipment. In the cell observation dimension, student 3 scores 9 points, showing high observation accuracy, while student 10 scores the lowest, only 5 points, which may affect the accuracy of his experimental results. **Figure 7** reflects the differences in students' experimental operation skills, indicating the effectiveness of teaching strategies in improving students' theoretical knowledge into practical skills, and the necessity of further guidance and training for different students. These data not only help teachers understand students' specific ability levels, but also provide important basis for future teaching plans.

Figure 7. Performance of 10 students in the experimental operation ability assessment.

7.3. Comprehensive ability assessment

The comprehensive analysis ability assessment mainly examines whether students can accurately interpret and analyze experimental results in combination with theoretical knowledge. After the experiment, students need to write a report to describe the experimental phenomena and process data, and use GraphPad to quantitatively analyze cell morphological changes. The assessment of the experimental report measures students' ability to use theoretical knowledge to analyze experimental data. This assessment reflects the effectiveness of the teaching strategy in cultivating students' independent thinking and problem-solving abilities, ensuring that they can not only perform experimental operations but also understand the scientific principles behind the experiments.

Table 4. Performance in the comprehensive analysis ability assessment.

Student ID	Experimental Group Cell Diameter (μm)	Control Group Cell Diameter (μm)	Report Score (Out of 10)
1	15.2	14.8	9
2	16.1	15.5	7
3	14.5	14.3	8
4	15.8	14.9	10
5	13.7	14	6
6	17	15.2	8
7	14.2	14.1	7
8	16.5	15.9	9
9	15.4	15	8
10	15	14.7	5

Table 4 shows the performance of the 10 students in the comprehensive analysis ability assessment, which is mainly analyzed through the cell diameter data of the experimental group and the control group and the report score. The cells in the experimental group are treated with specific mechanical forces and usually show more obvious morphological changes, such as an increase in cell diameter, indicating that the mechanical force has a significant effect on the cells; the cells in the control group are not disturbed by external mechanical forces and remained relatively stable. As can be seen from **Table 4**, student 4 performs best in terms of cell diameter in the experimental group, reaching 15.8 μm, and in the control group it is 14.9 μm, an increase of 0.9 μm, showing that the experimental treatment has a significant effect on cell morphology. The final report score is as high as 10 points, reflecting a excellent data analysis ability and application of theoretical knowledge. The cell diameter of student 2 in the experimental group is 16.1 μm and that in the control group is 15.5 μm. Although there is a certain increase, the report score is only 7 points, indicating that there is still room for improvement in data interpretation and logical argumentation. In contrast, the cell diameters of student 10 in the experimental group and the control group are 15.0 μm and 14.7 μm, respectively, with a small increase, and the report score is 5 points, indicating that there are major deficiencies in data processing and result analysis. Overall, the data in **Table 4** reflect the differences in students' experimental data analysis capabilities, and it can be seen that this educational strategy enables students to complete the experiment completely with good results.

7.4. Assessment of the accuracy of experimental results and data processing capabilities

The assessment of the accuracy of experimental results and data processing capabilities aims to detect whether students can obtain reliable data and conduct scientific processing. In the experiment, students need to precisely measure the area, perimeter, etc., of cell morphology, and make scientific judgments based on the data. Data processing requires the use of *t*-tests to ensure that the results are credible. Teachers assess by checking the data processing process, statistical analysis methods,

and result accuracy to determine whether the teaching strategy has improved students' rigor and scientific literacy in experimental design and result analysis.

Table 5. Changes in cell area and perimeter in the experiment.

Student ID	Original cell area(μm²)	Cell Area Change (Experimental) (μm²)	Cell Area Change (Control) (μm²)	Cell Perimeter Change (Experimental) ((μm)	Cell Perimeter Change (Control) ((μm)
1	420	150	130	48.5	45
2	460	200	180	50.2	47.5
3	390	175	165	49	46.8
4	480	220	190	52	48
5	400	160	140	47.5	45.5
6	405	180	170	49.5	46.5
7	408	190	175	50	48.5
8	433	210	200	51	49
9	450	155	150	48	46
10	380	165	155	49.2	47.2

Table 5 compares the changes in cell area and perimeter in the experiments of the 10 students to evaluate the effects of different treatments on cell biological characteristics. The area and perimeter of the two groups of original cells are basically the same, and the data are strictly measured with high precision. The analysis shows that the changes in cell area in the experimental groups are higher than those in the control group. The cell area change in the experimental group of student 1 is 150 μm^2, while that in the control group is 130 μm^2, and the percentage increase in cell area is 15.38%. This indicates that the cells in the experimental group grow more significantly after treatment. The further analysis shows that the cell area change in student 4 reaches 220 μm^2, with an increase of 15.79%. In terms of cell perimeter, the experimental group also shows a trend of being better than the control group. The perimeter change of student 1 is 48.5 μm, while that of the control group is 45 μm, with a perimeter increase of 7.78%. Overall, the cell perimeter change in the experimental group shows a more obvious increase, especially in student 4, whose perimeter change is 52 μm, an increase of 8.33% compared with 48 μm in the control group. After the application of mechanical force factors, the biomechanical response of cells is significantly improved, with the average cell area increased by 9.2% and the perimeter increased by 5.31%, and the students' completion level is also good. This effectively proves the positive role of cell biomechanics in understanding cell functions and improving practical ability, and also provides empirical support for the improvement of teaching strategies. Students' ability in experimental design and result analysis has been significantly improved.

8. Conclusions

From the perspective of cell biomechanics, this study uses AFM and confocal microscopy techniques to deeply explore the effects of mechanical force on gastrointestinal smooth muscle cells. Through quantitative analysis of cell membrane elasticity and cytoskeleton composition, this paper reveals the mechanical response

characteristics of cells under different mechanical stress conditions. The experimental results show that the teaching strategy combined with biomechanics significantly improves students' understanding of gastrointestinal function and practical operation ability. However, this study still has the problems of limited sample size and insufficient control of experimental conditions, which may affect the general applicability of the results. In the future, this paper plans to expand the sample size, further explore the mechanical properties of cells under different physiological states, and apply more interactive experiments in teaching to enhance students' practical experience and understanding of complex biological mechanisms. Through these improvements, it is hoped to provide a more solid foundation for the teaching and research of cell biomechanics.

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