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Incorporating a dynamic extraocular muscle simulation model into the undergraduate ophthalmic curriculum

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Abstract

Background Learning the anatomy of extraocular muscles and their coordination in eye movements is challenging for undergraduate medical students. We developed a dynamic extraocular muscle simulation model and integrated it into the undergraduate ophthalmic curriculum to evaluate its educational impact.

Methods A custom simulation model of binocular muscles was developed and assessed for educational effectiveness in undergraduate education. In a comparative study, 84 students from Peking Union Medical College were assigned to either the simulation group (one-hour didactic lecture followed by a half-hour simulator practice) or the traditional teaching group (one-hour didactic teaching followed by a half-hour video review). All students were given 5-point quizzes on the anatomical and functional basics of extraocular muscles before the lecture(Q1), after the lecture(Q2), and after simulator practice/video-review(Q3). Within each group, the scores of Q2 were compared with Q1, and the scores of Q3 were compared with Q2. The effectiveness of the simulation model was evaluated by comparing the improvements in scores from Q2 to Q3 between the two groups. Nonparametric tests were used for statistical analysis.

Results The simulation and traditional teaching groups were well-matched in terms of age, gender, Grade Point Average (GPA), and average Q1 and Q2 scores. The simulation group demonstrated significant improvements after both the didactic lecture and simulator practice. In contrast, the traditional teaching group showed significant improvement only after the lecture, not after the video review. The simulation model led to greater learning improvements compared to video review (mean(standard deviation)): 0.64(1.23) vs 0.05(0.79), $P = 0.006$.

Conclusions The extraocular muscle simulation model is a valuable adjunct to traditional teaching methods in undergraduate medical education. Simulation-based education should be encouraged for teaching complex anatomical topics.

Keywords Simulation, Undergraduate medical education, Extraocular muscle, Anatomy, Strabismus

Background

In undergraduate medical education, the anatomy of the extraocular muscles and their roles in eye movement is a fundamental part of both ophthalmology and neurology courses. This topic presents a significant challenge for novices. The depiction of anatomical illustrations, or the origin and insertion of extraocular muscles, is suboptimal

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using two-dimensional images. Furthermore, one single extraocular muscle plays multiple roles in eye movement, meaning that the contraction of one extraocular muscle can result in a combination of horizontal, vertical, and torsional forces. Additionally, the force generated by extraocular muscle contraction varies with changes in gaze, further complicating the learning process. Traditional teaching methods for extraocular muscle anatomy and function typically rely on didactic lectures, illustrating images, and animated videos. However, these methods alone have often proven insufficient for students to fully comprehend extraocular muscle contraction and their functional interrelationships.

Simulation models have been extensively employed in anatomy education. Studies have shown that interactive models can markedly enhance student engagement, understanding, and long-term retention across various domains of anatomy education [1, 2]. In response to the limitations of traditional teaching methods, several extraocular muscle simulation models have been introduced over the past decades [3–6]. While existing models in previous reports can illustrate the anatomy of extraocular muscles and their functional relationship in a monocular setting, none have been constructed on an orbit frame, nor have they incorporated binocular linkage. Therefore, there is still a noticeable gap between the expected teaching and actual instruction students receive.

The authors developed a binocular extraocular muscle simulation model constructed on a frame simulating the orbit. This study aims to assess the education effectiveness of our model among undergraduate medical students by comparing the performance of students who used the simulation model with those who received traditional teaching. The hypothesis is that our model will provide undergraduate medical students with a more authentic simulation-based learning experience and a superior grasp of the anatomical and functional basics of extraocular muscles compared with traditional teaching methods.

Method

Study design and participants

This comparative study was conducted at Peking Union Medical College with approval from the ethics committee of Peking Union Medical College Hospital. All participants were consented to their participation in the study.

A total of 84 undergraduate medical students were enrolled. The study was conducted during the "strabismus" lecture in the ophthalmology curriculum. Students were randomly assigned to the simulation group ($n=42$) and the traditional teaching group ($n=42$) using a computer-generated random number method. All participants were unfamiliar with the specific content of the topic before class. There were no significant statistical differences between the two groups in baseline characteristics such as gender, age, or prior course grade point averages(GPA).

Simulation model design

The simulation model is shown from anterior, lateral, superior, and posterior view (Fig. 1a-1d).The model consists of several components: a wooden frame simulating the bilateral medial and inferior orbital walls as well as the orbital apex; two metal rods on each side at an angle of 22.5°to the anterior/posterior axis; two plastic balls each anchored to the metal rod and covered by an outer spherical shell that can rotate freely around the inner ball; and twelve bands, each representing one of the extraocular muscles (lateral rectus, medial rectus, superior rectus, inferior rectus, superior oblique, and inferior oblique of both left and right eyes). The bands originate from the simulated orbital apex or orbital wall and attach to the appropriate positions on the spherical shell. Notably, the bands are designed to focus on the direction of muscle contraction relative to the globe. The "oblique muscles" are precisely aligned at an angle of 51° to the anterior/posterior axis. Each band can be manipulated individually or in combination, allowing for a three-dimensional representation of the relationship between extraocular muscle contraction and eye movement in a realistic and interactive manner. Notably, the model provides an intuitive illustration of binocular movements and the coordination of yoke muscles.

Quiz design

Three sets of quizzes (Q1, Q2, and Q3) were administered during the class. Each quiz comprised five questions (four multiple-choice questions and one fill-in-the-blank question) to be completed within 5 min. The quizzes were designed to assess students' understanding of extraocular muscle anatomy, the roles of extraocular muscles at different gaze directions, and the coordination of yoke muscles in binocular movements, targeting the specific learning difficulties reported by medical undergraduates. None of the questions were designed to evaluate the ability of undergraduates to apply the knowledge in clinical settings. Each quiz covered a variety of difficulty levels. Equal difficulty was ensured across the three quizzes, with no identical questions in different quizzes.

Experimental procedure

Both groups completed Q1 before the lecture. A one-hour lecture was then delivered concurrently to both groups. During the lecture, slides with text and images were used to present textbook knowledge. Students were

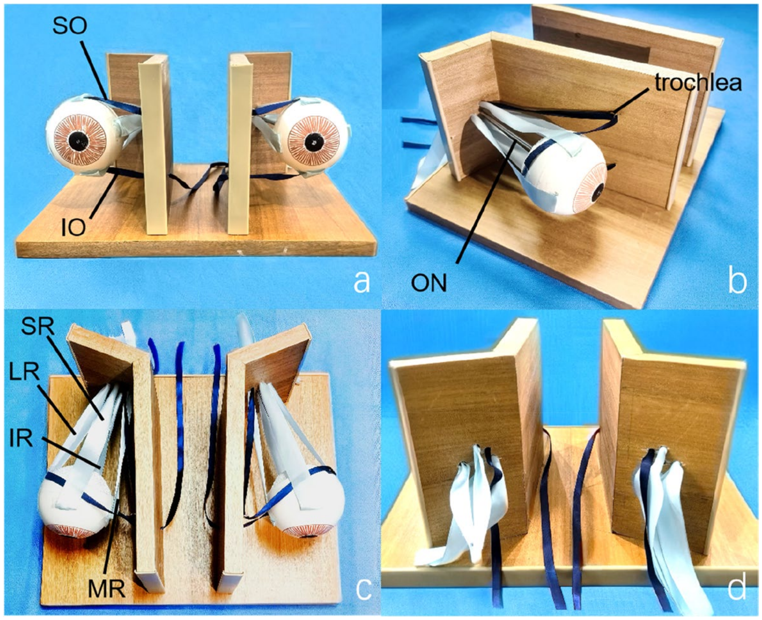

Fig. 1 The simulation model from (**a**) anterior, (**b**) lateral, (**c**) superior, and (**d**) posterior view. (SO, superior oblique; IO, inferior oblique; ON, optic nerve; SR, superior rectus; LR, lateral rectus; IR, inferior rectus; MR, medial rectus)

encouraged to ask questions during the lecture. After the lecture, both groups completed Q2. Subsequently, the simulation group participated in a 30-min hands-on session with the simulation model. During this session, the instructor first introduced the structure of the simulation model and demonstrated the role of each extraocular muscle using the model. The instructor posed questions (e.g., "Which muscles are involved in rotating the eye downward?" or "What is the function of the right superior oblique at primary gaze?") and guided the students through their answers. Students were then given opportunities to operate the model, discussing and asking questions freely. Meanwhile, the traditional teaching group was given a 30-min review period by watching a video presenting the anatomy and function of extraocular muscles in a separate classroom. Afterward, both groups completed Q3.

Statistical analysis

All quizzes were collected using an online software named "Wenjuanxing" and scored by instructors (one point per question, totaling five points per quiz). Student scores were recorded and analyzed using SPSS software (version 27.0; SPSS Inc., Chicago, IL, USA), with results expressed as mean(standard deviation, SD). Within each group, the paired Wilcoxon signed-rank test was used to compare scores before and after lecture, as well as before and after simulation/video review. The Mann–Whitney U test was used to compare scores between the two groups. A P-value of <0.05 was considered statistically significant.

Results

Intra-group comparisons

Quiz scores for both groups were analyzed and presented as mean(SD). In the simulation group, scores for the three quizzes were 3.17(1.45), 3.69(1.18), and 4.33(1.12), respectively. Paired Wilcoxon signed-rank test between Q1 and Q2, Q2 and Q3, as well as Q1 and Q3 all showed statistically significant increases ($P<0.05$) (Table 1), indicating that understanding of current topic was improved following the lecture and further improved by simulation. In the traditional teaching group, scores were 3.12(1.27), 3.67(1.10), and 3.71(1.11), respectively. Statistically significant increases were observed from Q1 to Q2 and from Q1 to Q3 ($P<0.05$). However, no statistically significant

Table 1 Comparison of quiz scores within the simulation group

Quiz	Mean(SD)	*P* -Value*
Q1	3.17(1.45)	
Q2	3.69(1.18)	
Q3	4.33(1.12)	
Q1 vs Q2		**0.004**
Q2 vs Q3		**0.002**
Q1 vs Q3		**< 0.001**

* paired Wilcoxon signed-rank test

difference was found between Q2 and Q3 (before and after video review) ($P = 0.682$) (Table 2), suggesting that video review did not further assist students in understanding the current topic.

Inter-group comparisons

When comparing the quiz scores between the two groups, no statistically significant differences were observed in the baseline scores (Q1) or the scores following the lecture (Q2). However, a significant difference emerged after the simulation or video review session, with the simulation group demonstrating superior performance compared to the traditional teaching group ($P < 0.05$) (Table 3).

Comparison of quiz score improvements between groups

The improvements in quiz scores from Q1 to Q2 (improvement after lecture), and from Q2 to Q3 (improvement after simulation or video review) were compared between the two groups. In the simulation group, the improvement was 0.52(1.13) from Q1 to Q2 and 0.64(1.23) from Q2 to Q3. In contrast, the traditional teaching group showed an improvement of 0.55(0.80) from Q1 to Q2, but only 0.05(0.79) from Q2 to Q3. The simulation group exhibited a significantly greater improvement from Q2 to Q3 compared to the traditional teaching group ($P < 0.05$) (Table 4), suggesting that the interactive simulation model was more effective as a teaching tool than the video review.

Discussion and conclusion

Our findings indicate that compared with traditional teaching methods, our eye-movement simulation model significantly enhanced students' quiz performance and deepened their understanding of the anatomy of extraocular muscles and their functional relationships in eye movement.

Clinically, misalignments of the two eyes can lead to diplopia and cosmetic issues. These patients may seek help from either an ophthalmologist or a neurologist. The differential diagnosis for ocular movement disorders largely relies on thorough physical examinations, such as nine-gaze photography, red glass test and Hess-Lancaster test in nine gaze positions. Proper interpretation of these tests depends on a comprehensive understanding of the complex forces generated by extraocular muscle contraction at different gaze positions. The spatial complexity of the anatomy and function of extraocular muscles makes traditional teaching methods insufficient to fully explain them from a three-dimensional perspective. Therefore, teaching the anatomy of extraocular muscles and their coordination in binocular movement is not only crucial but also challenging in medical education, especially at the undergraduate level.

Simulation-based education has been well-established in nearly all subspecialties of medical education, including ophthalmology [7]. Simulation can be achieved through dry-lab models [8], wet-lab models [9], or digital learning equipment [10]. In ophthalmology education, simulation is beneficial for illustrating anatomy [8], practicing physical examination skills such as direct ophthalmoscopy [11] and training diagnostic abilities [12] as well as surgical skills [13, 14]. Our findings align with previous studies showing that interactive simulation models enhance the comprehension of complex anatomical information [2]. The model provided an intuitive and immersive learning experience in the oculomotor system. The dynamic feature of the freely rotating "globe" controlled by "muscles" offers a clear visualization of eye movements and their underlying mechanics. The tactile and visual feedback from the "globes, muscles, and orbit walls" in our model not only simplifies complex

Table 2 Comparison of quiz scores within the traditional teaching group

Quiz	Mean(SD)	*P*-Value*
Q1	3.12(1.27)	
Q2	3.67(1.10)	
Q3	3.71(1.11)	
Q1 vs Q2		**< 0.001**
Q2 vs Q3		0.682
Q1 vs Q3		**< 0.001**

* paired Wilcoxon signed-rank test

Table 3 Comparison of quiz scores between simulation and traditional teaching groups

Quiz	Simulation group ($n = 42$)	Traditional teaching group ($n = 42$)	*P*-Value#
Q1	3.17(1.45)	3.12(1.27)	0.703
Q2	3.69(1.18)	3.67(1.10)	0.813
Q3	4.33(1.12)	3.71(1.11)	**0.004**

Mann–Whitney U test

Table 4 Comparison of the quiz score improvement from Q2 to Q3 between simulation and traditional teaching groups

Score improvement between quizzes	Simulation group ($n = 42$)	Traditional teaching group ($n = 42$)	*P*-Value#
Q2-Q1	0.52(1.13)	0.55(0.80)	0.724
Q3-Q2	0.64(1.23)	0.05(0.79)	**0.006**

Mann–Whitney U test

anatomical concepts but also promotes active learning, contributing to a deeper understanding of muscle contraction and their functional relationships.

Several eye-movement simulation models have been reported in previous literature. In 1965, Williams described a prototype of a working model [3]. This model consisted of a hardwood ball with a brass cup, several rubber bands, and a base, representing the globe, the rectus and oblique muscles, and the orbit floor, respectively. Several strings were attached to the ball and users could pull strings to induce eye movement. In 2018, Wood and Dayal introduced a revised version of the model by Williams, where the rubber bands mimicking muscles could be pulled directly to generate eye movement [4]. Xiong et al. reported an electric ocular movement simulation system in 2019 [5]. Khadia also reported a simple simulation model for extraocular muscles in 2023 [6]. These models are more realistic than illustrative images, videos, or virtual reality (VR) models. However, some teaching challenges remain unsolved. Firstly, the medial orbit wall was not included in previous models, which is essential for illustrating the origin of the inferior oblique muscle and the trochlear of the superior oblique muscle. Secondly, previous models were monocular, increasing the spatial imagination difficulty for beginners, and failing to explain how yoke muscles coordinate in binocular movements. Thirdly, the globes in previous models were 3 inches or 60 mm in diameter, which is relatively small for classroom use. Our model made several improvements over previous models. Firstly, we constructed a vertically placed wood plate on the base to simulate the medial orbit wall. Secondly, this was a binocular model, including two "globes" and two sets of "muscles". Such a binocular model with essential orbital structures is more readily comprehensible to beginners. Thirdly, in the current model, the globe diameter was 100 mm, larger than in previous models. The adequate size ensured a clear illustration in a classroom setting and increased the ease of manipulation.

Digital three-dimensional models of extraocular muscles have also been reported [12, 15, 16]. These models are based on VR techniques and allow for interactive learning processes. As a cutting-edge educational technology, VR simulation effectively enhances trainees' skills. Compared to traditional hands-on simulation, VR offers the benefits of an immersive and interactive learning experience, along with the capability for electronic recording of results [17]. However, there are instances where VR simulation does not facilitate learning as effectively as hands-on methods. For example, in a basic life support course conducted by Issleib et al., the flow time, a crucial indicator impacting survival rates, was found to be inferior in the VR teaching model compared to physical hands-on training. This finding underscores the need to carefully consider the differences between VR simulation and real-life scenarios [18]. Additionally, hands-on simulation demonstrates advantages over VR simulation in terms of cost, intuitiveness, and the avoidance of eye strain [19].

Although simulation models improved students' knowledge, they should not replace traditional teaching methods in undergraduate education. According to cognitive load theory, instructors should optimize the design of simulation by minimizing extraneous cognitive load [20, 21]. Undergraduate students unfamiliar with the topic should be given a lecture on the basics of the terminology, definition, and innervation of extraocular muscles, providing a preparatory overview before the simulation session.

There are several limitations in the development of the model. Firstly, the superior and lateral "orbit walls" were not included in the current model to ensure easy visualization of the extraocular muscles. Future models should incorporate plates or three-dimensional print technology to construct the entire orbit structure, enhancing the realism of the current model. Transparent materials could be utilized to optimize visualization of the inner structure of the model. Secondly, the attachment of "muscles" on the "globe" should be firmer and more durable. Thirdly, the rotation of the shell sometimes produced distracting noise. There are also several limitations in the study design. First, the number of participants is limited. Second, potential confounding factors, such as the lack of interactive learning experience and real-time discussions in the video group, should be balanced in future studies by providing interactive video and more discussion opportunities. Third, given limited time during class, we included only 5 questions on basic knowledge in each quiz. Future studies using practical exams or qualitative interviews will give a more comprehensive evaluation of the model's effectiveness. Fourth, the teaching efficacy was compared to a single traditional teaching method instead of various other pedagogical strategies. Moreover, the effectiveness of our simulation model was only evaluated in a large-class setting. Future studies should assess learning outcomes in small group settings and evaluate long-term knowledge retention.

In conclusion, this study demonstrates the effectiveness of a custom-made simulation model of binocular extraocular muscles in providing an intuitive illustration of extraocular muscle contraction in eye movement and offering an interactive learning environment that facilitates self-reflection and peer discussion. This study contributes to refining educational strategies and tools in undergraduate medical education by presenting a more effective approach for teaching complex anatomical concepts.

Abbreviations

GPA Grade Point Average
SD Standard Deviation
SO Superior oblique
IO Inferior oblique
ON Optic nerve
SR Superior rectus
LR Lateral rectus
IR Inferior rectus
MR Medial rectus

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Authors' contributions

Erqian Wang designed and constructed the model, conducted the classroom teaching, drafted the background and discussion part of the manuscript, and revised the entire manuscript. Qianyi Yu designed grouping of students and the procedure of classroom teaching and quizzes, collected data, carried out literature search, and drafted the methods and results part of the manuscript. Haiyan Xu, Shuang Geng, and Enhua Shao contributed to model design and optimization, and participated in the model demonstration section of classroom teaching. Zhikun Yang coordinated in the classroom teaching and participated in the drafting and revision of the manuscript. Meifen Zhang identified the deficiency of effective simulation models during classroom teaching for ocular movement, proposed a concrete plan for incorporating the current model into classroom teaching, and revised the manuscript. Hui Li led the design of the model, provided suggestions during multiple iterations of model optimization, and revised the manuscript. All authors read and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate:

This study has been approved by the Ethic Committee of the Peking Union Medical College Hospital, China (No.I-24PJ1739). The study protocol was conducted in accordance with the principles described in the Declaration of Helsinki. All participants were fully informed and consented to their participation in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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