Impact of Simulation Software Integration on Student Perception and Academic Performance in Medical Undergraduate Physiology and Biophysics Course

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Abstract

Current computer development offers an overwhelming amount of simulation software in medical education and biomedical sciences, characterized by ease of use, free access, an excellent cost-benefit ratio, optimized session time, student engagement, motivation for creativity, self-training enhancement, and immersive teaching that covers most biomedical topics. Here, a total of 853 undergraduate medical students from a physiology and biophysics course, who were rotating through a module that included simulation software, in addition to conventional experiment-based teaching, were evaluated, along with 2095 students rotating in the other seven modules without simulation software. This evaluation was conducted using a perception survey and final module grades. The results show higher perception survey scores and final module grades for the group with added simulation software strategies compared to those who did not. Additionally, both groups demonstrated a high correlation between perception survey scores and final module grades, which were best described by second-order polynomial regressions. Overall, students exposed to the simulation software exhibited greater perception and achieved higher grades, with perception strongly linked to student performance in both groups.

Keywords: Biomedical simulation software, Undergraduate medicine, Health sciences teaching.

1. Introduction

Current Scenario of Medical Teaching and Research

The development of computing over the last 30 years, the need to find alternatives to animal research or to reduce its cost for undergraduate teaching, and the rapid testing of theoretical models have generated a branch of computing and mathematics dedicated to the production of simulation software (SSs). These programs incorporate mathematical equations that describe a specific model or biomedical process, capable of reproducing its performance and providing graphical and/or analytical results (1) . The equations used in SSs closely demonstrate basic, general concepts, and/or fundamental biomedical laws, because they are defined by multiparameter regression analyses of real data obtained in experiments, which gives them intrinsic validation (2). The accuracy of SSs results depends predominantly on the accuracy of the regression analyses that generated their equations (2). Additionally, since regression equations are multiparameter, it is possible to modify one or more parameters in the simulation, thus obtaining results for comparison and progression of different scenarios (2–4). This capability confers SSs the status of definable objects, similar to that of many toys used as instructional tools, allowing the virtual or analog reproduction of real-world situations (5).

The current approach to science teaching should focus on personalized, inquiry-based, technology-integrated learning, incorporating hands-on experiments to promote active participation. Teaching should shift away from rote memorization toward fostering conceptual understanding, critical thinking, and practical application in the real world. Modern science education encourages immersive experiences with virtual labs, augmented reality, and virtual reality, as well as interactive simulations, to engage students in a deep and meaningful way. Collaborative learning methods and interdisciplinary approaches are also essential trends, promoting teamwork, communication, and broader connections between scientific concepts and other fields (3,5–7).

Current SSs offer a wide range of graphical possibilities that go beyond the mere presentation of results on Cartesian axes, but present animations, displacements, and synthetic and volumetric images, both two- and three-dimensional, with great precision and with time scales chosen by the user (7). SSs developed for biomedical sciences are currently available, both commercially and as free software at no cost; these are generated by universities and laboratories for academic purposes, with a long list of offerings (6,8–11), unfortunately, very dispersed on the web, requiring a systematic and long-term search (8).

In biomedical teaching and research, no institution, including the world's top 10 universities, has sufficient funds for equipment, reagents, researchers, and teachers to cover all the program contents of basic science and clinical subjects such as Physiology, Biophysics, Biochemistry, Pharmacology, Microbiology, Parasitology, Pathophysiology, Immunology, Medical Imaging, and Histology, to name just a few. Moreover, when the institutional financial resources are not enough to support only a few experimental instructional components of the program, the situation turns to the dangerous theory-only medical teaching, frequently seen in third-world countries (12). This contrasts with the fact that all instructional objectives contained in these teaching programs must be mandatorily achieved, as required by current accreditation criteria and standards, in which, in addition, interdisciplinarity and transdisciplinarity are the predominant view for attaining sustainability in science teaching, this because no strategy based on a single discipline will be efficient, on the contrary, those that include a greater number of disciplines will proportionally approach the desired achievement (12–14).

The potential academic overload, i.e., insufficient academic positions, lectures, exam preparation and correction time, academic meetings, and even docent capacitation, progressively reduces the available time to maintain and incorporate new, practical, and effective sessions (12,15).

The aforementioned implies a paradigmatic shift in the current teaching-learning process in biomedical sciences, due to the rapid renewal of knowledge, as well as to the teaching strategies themselves. These factors, combined with the time demands placed on faculty by university management, are considered as the dedication to preparing assessments, marking them, and providing the feedback required for constructive evaluation and performance monitoring, frequently generate a paradigmatic faculty paralysis, causing them to cling to their comfort zone, maintaining outdated or inefficient instructional strategies. One way to overcome this paralysis is the very valid argument of returning to the very roots of science teaching based on experiments, now, as proposed in the present report, renewed using SSs teaching methods.

Undergraduate medicine school scenario

The Department of Physiological Sciences within the Health Sciences Faculty of the Universidad de Carabobo, Venezuela, offers courses in Physiology and Biophysics as part of the undergraduate medical program. It is in the second year of the program and requires passing the first-year anatomy, histology, and mental health courses as prerequisites. The Physiology and Biophysics program, from 2000 to 2010, enrolled approximately 350 to 400 students annually, teaching them the subjects of General Physiology, Medical Biophysics, Neurophysiology, Digestive Physiology, Respiratory Physiology, Renal Physiology, Cardiovascular Physiology, and Endocrine Physiology. The course was taught by seven medical specialists and professors holding positions associate Professor, or Full Professor level, half of whom held a PhD degree. All of them had at least one year of teaching training courses from the University's Faculty of Education. These lecturers taught the module corresponding to their specialty for three weeks, comprising a total of 6 hours of theoretical instruction and 12 hours of practical sessions. Each lecturer taught the General Physiology Module during the first 4 weeks of the course and then continued with their specialty module. Each module had a weekly cumulative assessment, and the module grade was obtained by averaging these three assessments. The student groups rotate sequentially for each module. Additionally, midterm assessments were given after modules 4 and 8, and a final exam was given at the conclusion of all modules. The final course grade was calculated as the average of the module grades (40%), the midterm exams (30%), and the final exam (30%).

This report examines the perception of medical undergraduate students of the use of SSs as a learning tool and its impact on course grades.

2. Materials and methods

Standard instructional strategies and simulation software tested

All modules of the Physiology and Biophysics subject in the undergraduate medical program include theoretical and practical sessions with *in vivo* and/or *in vitro* demonstrative experiments, which are performed in teaching and research laboratories, as well as clinical assessment sessions, such as ECG (16,17), EMG (18), EEG (19,20), NCV(18), SSEP (21), neuronal recording and analysis (22,23), abdominal ultrasound (24,25), balistocardiography (25), clinical campimetry (26), ion transport in membranes, intestinal glucose absorption, gastrointestinal physiology (27-29), arterial pressure, plethysmography, vestibulography, spirometry, medical radiophysics (30-32), immunology (33), low-density lipoprotein cholesterol estimation (34), cardiac auscultation, as well as videos of experimental sessions.

Since 1995, the practical session of the neurophysiology module includes experimental *in vivo, in situ,* and *in vitro* recording of action potentials in sensory neurons, animal and human somatosensory evoked potentials (SSEP), clinical electromyography (EMG), clinical electroencephalography (EEG), median nerve conduction velocity (NCV), electrical muscle stimulation (FES) and somatosensory evoked potentials (SSEP). Additionally, this module incorporated the use of SSs, including recording local potentials (Resting, PSEP, PSIP), ionic dependence of the action potential, evaluation of refractory periods, the effect of agonists and antagonists on the motor end plate and their effects on skeletal muscle contraction, ion channel kinetics, voltage clamp, organ bath and the study of agonists and antagonists in vascular, skeletal, and intestinal muscle contraction, and neural networks (35-37). The SSs used in this module were obtained from the Biomedical Simulation Software Link Repository, which is currently freely accessible on the Translational Neuroscience Lab website (https://sites.google.com/view/translational-neuroscience-lab/simulation-software), located at the Instituto de Ciencias Biomedicas, Universidad Autónoma de Chile. From this repository, the software NeuroSim v.4 (11) was selected on the date of the data collection. These SSs were presented in 60-minute practical sessions per week, alternating with other real experimental sessions. It is worth noting that all SSs are freely accessible to students and academics. The supporting equipment consists of a modest laptop computer (Celeron M, 1.6GHz, 40GB HD, 440MB RAM, running Windows®), a Video Beam projector, and a laser pointer.

Evaluation of the SSs application

The Department of Physiological Sciences conducts a student perception survey at the end of the course, following the final exam, as part of the course evaluations. The survey consisted of a Likert scale ranging from 0 to 5, with 0 indicating the worst perception and 5 indicating the best, summarized in a single numeric response.

In the present study, the student perception survey and final module grade from the neurophysiology module, where SSs were applied (in the SSs group) and the rest of the modules (in the non-SSs group), were examined using data from two randomly selected non-sequential course years. Because all students rotated through all modules, those included in the neurophysiology module were also included in their rotations in the other modules. The data was anonymized and encrypted to prevent traceability, as stated in the informed consent and approved by the institutional bioethics committee.

Statistics

Descriptive statistics of the survey and grade obtained in the With SSs and Without SSs groups were estimated. The non-Gaussian distribution of the data was tested using the Shapiro-Wilk test. The Mann-Whitney test was used to assess statistical differences between the two groups. Correlation and regression analysis were applied between the perception survey and module grade in each group, using the p-value and R-squared value as the criteria for determining the best curve fit. The statistical significance level was set at $p < 0.01$. PAST v.5.2.1 statistical software was used.

3. Results

Statistical description of the study groups

A total of 853 students from the With SSs group and 2,095 students from the Without SSs group, both from two non-sequential year courses, were evaluated. These differences are because the first was constituted only by data from students rotating through the neurophysiology module. In contrast, the other group consisted of all students rotating through the other seven modules.

Table 1 presents the central tendency and dispersion values of the perception survey and module final grade from the With SSs or Without SSs groups.

Table 1. Descriptive statistics of the perception survey and final module grade of the With SSs and Without SSs groups

	With SSs		Without SSs	
Parameter	**Perception**	**Module Grade**	**Perception**	**Module Grade**
N	853	853	2095	2095
Mean	4.73 *	16.66	4.38 *	14.37 *
SE	0.02	0.02	0.01	0.01
SD	0.47	0.58	0.63	0.73
Median	5 *	17 *	4 *	14 *
25th percentile	4	16	4	14
75th percentile	5	17	5	15
Coeff. Variation	9.95	3.48	14.48	5.09

Maximal grade is 20 points.

Group comparisons

The comparison of the Student Perception Survey between modules With SSs and Without SSs is presented in Figure 1, which shows the statistically significant ($p<0.001$) higher perception value of the student for the With SSs module. (+20%; $p<0.001$). Figure 2 presents the module final grades of the two groups, showing that students from the With SSs group have significantly higher grades (+15.9%; $p < 0.001$) than those from the Without SSs group.

Intragroup perception – grade correlation and regressions

Figures 3 and 4 display the scatter plots, statistically significant coefficient of determination (r^2), and curve fitting between the perception and final module grade for the With SSs and Without SSs groups, respectively. The results show a significantly high correlation between module grade and the perception survey variables.

Fig. 1. Comparison of the Student Perception Survey between the modules with SSs and without SSs groups. Values were obtained from the Perception survey. Bars represent mean values, and whiskers represent standard error. Differences are highly significant ($p<0.001$; Mann-Whitney Test).

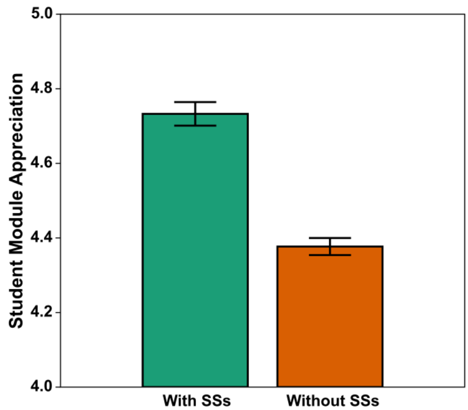


Fig. 2. Comparison of the Student final module grades between the With SSs and the Without SSs groups. Bars represent mean values, and whiskers represent standard error. Differences are highly significant ($p<0.001$; Mann-Whitney Test).

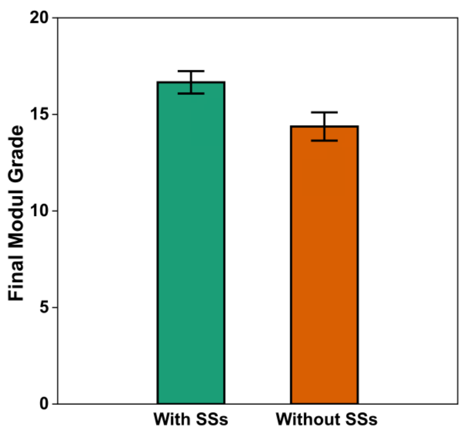


Fig. 3. Scatter plot of the module grades and perception survey values from the With SSs group, a statistically significant ($p<0.0001$; $F = 448.12$) coefficient of determination (r^2) = 0.51, coefficient of correlation = 0.72. The regression equation (displayed) was best fitted to a second-order polynomial function. The highly overplotted points were partially visualized by jittering.

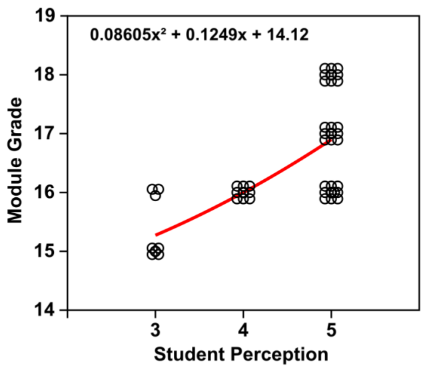
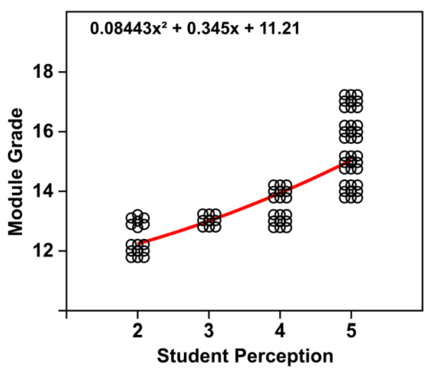


Fig. 4. Scatter plot of the module grades and perception survey values from the Without SSs group, a statistically significant ($p<0.0001$; $F>1000$) coefficient of determination (r^2) = 0.82, coefficient of correlation = 0.90, and the regression equation (displayed) was best fitted to a second-order polynomial function. The highly overplotted points were partially visualized by jittering.



4. Discussion

The present study evaluates the implementation of simulation software into the Physiology and Biophysics course program of a medical undergraduate program. The simulation program did not substitute any of the current practical/experimental sessions but was added. The student perception of this implementation was higher than for the other traditional modules and had a significant impact on obtaining better module grades. Additionally, a highly significant correlation was found between perception and grades for both groups, allowing us to estimate one of the measured variables from the other.

From an operational perspective, during the use of the SSs, students' attention is focused on the principle to be demonstrated. There are no distractions such as preparatory procedures for the practice, i.e., dissections, perfusions, cable connections, fluid lines, waiting for stabilization, calibration, and similar procedures that, despite being experimentally necessary, distract students from the central idea of the practice. The SS, while presenting the experimental setup, does so in a concrete and concise manner, quickly moving to the experiment and its results, which allows for a more efficient use of time and enables a significantly greater number of tests than would be possible with real experiments. It is possible to reproduce comfortably, in a single practical session, the same sequence of many experiments that led to the discovery of fundamental laws and principles of biomedical sciences, thereby significantly optimizing teaching time. This characteristic, combined with the relatively low cost of the computer-projection equipment, ultimately constitutes an excellent cost-benefit ratio, to which must be added the absence of animal sacrifice (1,5,6,13,14). The results reported here, in the context of the undergraduate medical neurophysiology teaching, support the educational value of the SSs use (38-40).

In our opinion, the most valuable teaching characteristic of using SSs is their interactivity. Thanks to this, practical sessions become true discovery laboratories for students, where any concern, idea, or doubt can be immediately tested, discussed, and interpreted, with conclusions that demonstrate the laws and principles being taught, capturing the attention of all students intensely. Thus, one of the requirements of modern teaching of physiological sciences is active participation in decision-making in experiments.

Another factor contributing to the proposal of using SSs is to promote the democratization of science by implementing policies and strategies that achieve a conceptually open and freely accessible science, both in general and specifically in biomedical science. That is, science that is not subject to the availability of monetary resources. By this, we mean free access to journals, books, instructional resources, experiences, and exchanges, among other crucial elements. In these respects, universities and governments have initiated these strategies. A good example of this is the instructional resources, which, in the form of simulation software, are described here and are freely or at low cost accessible, even to the general population.

In several countries, health research projects funded by any source are increasingly led by professionals other than physicians. They are currently led primarily by experts in biology, bioengineering, medical technology, biochemistry, immunology, physics, and microbiology, among other fields. While they may possess greater technical competence, they lack the biopsychosocial vision of the physician, which we have already proposed as a successful comprehensive approach that the World Health Organization has requested since the last century (41). It is essential to highlight that this phenomenon is a result of the predominance of clinical care in the medical curriculum at the expense of experimental and practical activities in basic science subjects. The very negative aphorism supports this: "The important thing is to care for patients, not the theory of basic sciences." This is taken to the extreme by the preparation of an undergraduate thesis or research activity (both in undergraduate and graduate medical programs). Given the lack of funding resources, research teams, or mentors (both in quality and quantity), it becomes, in most cases, a kind of torture, which, far from attracting students to biomedical research, ultimately drives them away from it. Reversing this phenomenon, as well as promoting biomedical research among medical students and graduates, requires multiple and simultaneous measures applied to faculties, that should be understood as part of the process of optimizing the use of simulation software in medicine and therefore not strictly necessary for their use, since it is very likely that all universities and medical schools already have the operational capacity installed for this purpose, that is, the minimum requirement of having a computer and a projector connected to it (8). We must also consider the increasingly intense budgetary restrictions faced by university institutions, as well as the progressive decline in dedication to teaching and/or scientific research among practicing physicians. This creates a highly adverse environment for practical activities, demonstrative experiments, or individualized experiments, which are increasingly being replaced by mere theoretical classes and/or the presentation of videos obtained from the internet.

Our results also support the notion that the combination of digital platforms used for remote learning (e.g., Zoom, Canvas, Teams) combined with real and SSs presents a significant opportunity to incorporate laboratory experimentation of varying complexity into undergraduate and postgraduate medical education with good outcomes (39,40,42,43). SSs, compared to expensive and varied laboratory equipment, require few resources: a computer and a projection system, which, in terms of cost, represents a tiny fraction of the laboratory budget needed for a single experimental setup. Additionally, the same presentation system can be used with different SSs covering different topics in various courses within the program (43).

Institutionally, a university with severe budgetary constraints could, with SSs, not only maintain its academic level but even improve it by incorporating a greater number and quality of practical sessions in each course to achieve the proposed instructional objectives. This is a real possibility given the wide variety of SSs available, which cover most of the subjects taught in Biomedicine programs (39,42,44).

Funding and financing for biomedical scientific research, in general, for undergraduate and graduate medical faculty are limited in the number of annual calls and are highly competitive. As there are generally restricted on prior scientific experience, the most productive researchers are more likely to be awarded funding. Funding is also limited to specific topics that do not always align with personal interests, and finally, there are very rigid planning and execution requirements.

Given the conventional difficulties described above, the use and application of experimental simulation software as a research tool offer undergraduate and graduate medical faculty the following advantages:

1. They do not depend on funding sources for research projects, as they already have the installed capacity for their use.
2. Simulation software is based on mathematical models validated through peer-reviewed scientific publications in indexed journals, which guarantees their fidelity to real-life processes and, therefore, their publication.
3. Currently, 20% to 30% of indexed publications use simulation models.
4. Excellent cost-benefit ratio
5. Excellent time-to-results ratio (High time efficiency).
6. Allows pilot testing as a pre-validation of the project in real-life prospective experimental studies.
7. Allows rapid hypothesis testing.
8. Allows rapid generation of project variants by evaluating the effect of parameter modifications in the simulation scenario.
9. Provides an open door to generating new research projects, given their dependence on user creativity.
10. Provides portable laboratories that allow researchers to conduct their experiments anytime, anywhere, enabling project monitoring and continuity.

The use of simulation software in biomedical teaching offers the following advantages:

1. They are based on mathematical models validated through peer-reviewed scientific publications in indexed journals, ensuring their fidelity to real-life processes.
2. During use, the student/participant is not dazzled or distracted by the paraphernalia of the laboratory environment (cables, procedures, gloves, lenses, preparatory procedures, etc.). Instead, their attention is focused on the critical aspects of the experiment (intervention, dose, effect, etc.) and, especially, on its results, without losing sight of the experience itself.

3. Its application focuses on achieving the instructional objectives to be taught.
4. Excellent value for money.

However, all these potential benefits depend on the teacher's capacity, their scientific knowledge, and handling of the interactivity during the simulation, among others (8,42,44,45).

5. Conclusion

A total of 853 students rotating through a module that included simulation software and 2,095 students rotating in the other seven modules, which included only traditional experiment-based teaching strategies, were evaluated. The results showed higher mean perception survey scores and final module grades for the group with added simulation software strategies compared to those who did not. Additionally, both groups demonstrated a high correlation between perception survey scores and final module grades, which were best described by second-order polynomial regressions. Overall, students exposed to the simulation software exhibited greater perception and achieved higher grades, with perception strongly linked to academic performance in both groups.

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