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The Use of Dynamic 3D Printed Cervical Spine Models in a Musculoskeletal Physical Therapy Course

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Abstract

Purpose: While mass-produced anatomical models are commercially available, many models are inflexible and static, and may not meet the needs of health professions students. Advances in three-dimensional (3D) printing have demonstrated tremendous potential for enhancing student learning. This study uses 3D printed cervical spine models to explore whether use of dynamic, flexible models improve student learning in a cohort of physical therapy students. Methods: 3D printed models of the cervical spine and occiput were printed using a fused deposition modeling 3D printer and polylactic acid filament, and augmented with hook and loop fasteners, foam sheets, and cords to simulate structures such as ligaments, intervertebral discs, and the spinal cord. Twenty-one second-year students enrolled in a Doctor of Physical Therapy musculoskeletal course were divided into two groups: one group had access to the augmented 3D printed models (n=11) and the other had access to commercially available models (n=10). A 10-question multiple-choice assessment was given on the cervical spine and its arthrokinematics before and after lectures and manipulation of cervical spine models. Four Likert-scale questions measuring confidence in explaining or performing a particular cervical spine movement and palpating bony landmarks were also queried. Results: There were no significant differences in the post-test scores for the dynamic and static model groups ($t=.66$, $df=19$, $p=0.52$), or in the confidence in explaining cervical spine movements when comparing the type of model used. Conclusions: This study did not replicate others' findings of the effectiveness of dynamic 3D printed models. Factors may include that the length of time students manipulated models was unknown, that other studies compared 3D printed models and non-3D printed models (cadaveric donors, plastinated models, 2D images), and that 3D printing is not as effective for all anatomical regions. Despite the lack of significant differences, use of dynamic 3D printed models did not hinder learning and may complement other resources available in physical therapy educational settings.

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ABSTRACT
Purpose: While mass-produced anatomical models are commercially available, many models are inflexible and static, and may not meet the needs of health professions students. Advances in three-dimensional (3D) printing have demonstrated tremendous potential for enhancing student learning. This study uses 3D printed cervical spine models to explore whether use of dynamic, flexible models improve student learning in a cohort of physical therapy students. **Methods:** 3D printed models of the cervical spine and occiput were printed using a fused deposition modeling 3D printer and polylactic acid filament, and augmented with hook and loop fasteners, foam sheets, and cords to simulate structures such as ligaments, intervertebral discs, and the spinal cord. Twenty-one second-year students enrolled in a Doctor of Physical Therapy musculoskeletal course were divided into two groups: one group had access to the augmented 3D printed models (n=11) and the other had access to commercially available models (n=10). A 10-question multiple-choice assessment was given on the cervical spine and its arthrokinematics before and after lectures and manipulation of cervical spine models. Four Likert-scale questions measuring confidence in explaining or performing a particular cervical spine movement and palpating bony landmarks were also queried. **Results:** There were no significant differences in the post-test scores for the dynamic and static model groups (t=.66, df=19, p=0.52), or in the confidence in explaining cervical spine movements when comparing the type of model used. **Conclusions:** This study did not replicate others' findings of the effectiveness of dynamic 3D printed models. Factors may include that the length of time students manipulated models was unknown, that other studies compared 3D printed models and non-3D printed models (cadaveric donors, plastinated models, 2D images), and that 3D printing is not as effective for all anatomical regions. Despite the lack of significant differences, use of dynamic 3D printed models did not hinder learning and may complement other resources available in physical therapy educational settings.

Keywords: 3D printing, physical therapy, education, learning

INTRODUCTION

Active learning is a student-centered educational technique incorporated throughout a variety of classroom settings. The benefits of active learning are numerous but can include metacognitive assessment, societal collaborative interactions, more in-depth processing, and increased physical interaction.[1] A meta-analysis by Freeman and colleagues found that students who participated in science, engineering, and mathematics courses relying solely on traditional lecturing (i.e., teacher-centered education) were, on average, 1.5 times more likely to fail than students who had courses that incorporated active learning.[2] Students who participated in active learning exercises (e.g., audience response systems, collaborative learning, and tutorials completed in class) received higher grades than those who did not, demonstrating the academic benefits for students who participate in active learning techniques. While students perceive that they learn more about a topic when material is presented in a traditional learning (lecture-based) format, examination scores reveal the contrary: that those who participate in a student-centered active learning approach earn higher scores than students instructed by traditional means.[3] With lecture-based learning, students are shown one method of problem solving and may have difficulty with future scenarios because they were not taught to think outside of the box and more actively problem solve. During the collaborative efforts that take place between students in active learning sessions, students may be better able to recognize strengths and weaknesses in their knowledge base and develop new strategies to minimize gaps in knowledge.[4]

An additional concept related to student learning is cognitive load. Cognitive load pertains to the mental resources in one's working memory to carry out a task, and is made up of intrinsic load, extraneous load, and germane load.[5] Cognitive load is understood to be the sum of intrinsic and extraneous factors, which have the potential to overload and limit the functional ability of our working memory.[6,7] A systematic review looked at cognitive load theory in health science education, and found it to be very high due to the number of advanced concepts to learn and the need to manage a great amount of assigned work.[8] This systematic review defined intrinsic load as the task performance, while the germane load is how an individual learns a task so as to become autonomous in replication of that task. Extraneous loads are anything in the environment that can affect learning a task. It is thought that if one can limit how much extraneous load occurs during the learning process that intrinsic and germane loads can be optimized, thereby benefitting the learner's ability to complete the specific task.[9,10] Mental imagery or being able to visualize the concepts being taught are useful techniques to optimize germane load, due to the fact that neural circuit pathways, consisting of sensory, motor, executive, and decision-making, are promoted[8]. Thus, to have an optimal learning environment, there needs to be limitations on extraneous loads, the learner's intrinsic loads need to fit their stage of learning, and there needs to be activation of the germane load of the learner.[8]

In the last decade, three-dimensional (3D) printing technology has become a breakthrough among a sea of rapid prototyping technology, impacting a myriad of disciplines including healthcare. 3D printing technology is also known as additive manufacturing, and can print a physical object layer by layer using a computer-aided design or—after digital file conversion—from CT scans.[11] Prints can be made using a variety of materials, including thermoplastics, metal, and ceramics.[11] In health sciences education, 3D printed models have been touted as one form of active learning, as well as a potential means to reduce one's extraneous load.[12] The reduced cost of 3D printed models compared to commercially available models, and their durability, accuracy, and improved computer engineering programs to render bespoke models contributes to its application in educational contexts.[13,14] A 3D printed model can allow a student to study structures and visualize anatomical relationships more easily than using a two-dimensional (2D) image, providing an opportunity for students to interact with material.[15] Pedagogical studies demonstrate that the use of manipulatives improves student learning, regardless of subject content.[16,17] Students score higher on assessments when learning from hands-on activities compared to students who rely on virtual models or textbooks to study.[13,18,19] Due to their cost effectiveness, 3D printed anatomical models represent learning resources that students can attain for studying outside of the lab environment. Many commercially available models cost hundreds of dollars, and while some institutions can afford this expense, it is beyond the budget of the majority of students.[20] With many university and public library systems offer 3D printing services or a "Makerspace" for free or for a nominal fee, it is now possible for students to create their own models for studying at home.[21] Models can be printed at disproportionate amounts, printing more models of particularly challenging anatomical structures that may need more eyes and hands on the material.

With the cost of 3D printers and materials decreasing and the resolution of prints improving in recent years, technology has advanced to allow for the creation of dynamic, flexible models made from multiple materials. In healthcare education, it would be most advantageous to manufacture dynamic models that move in ways akin to how patients move in real life. Some 3D printers allow for multiple colors and materials to be employed, with more realistic renderings possible.[20,22,23] Smith and Jones' printing of the vocal apparatus using both rigid and flexible filament serves as a proof of concept that models made from the dual extrusion method save time during printing and post-processing; furthermore, it has the potential to yield more realistic anatomical models not currently available on the commercial market.[19] Given its rigidity, bone is the easiest to replicate in a 3D printing environment. But given that bones do not exist in isolation within the body, advances in materials that can represent ligament, cartilage, and meniscus must be explored. In the absence of a printer with the ability to print multiple materials, 3D printed models can be cheaply modified after printing using magnets, hook and loop fasteners, and other ordinary materials to mimic realistic movements.[22,24,25] For physical therapy students in particular, a thorough understanding of arthrokinematics is required, with a deep appreciation for how joint surfaces articulate and ligaments assist in stabilizing joints, thereby limiting movement.

Several studies have evaluated the effectiveness of 3D printed models, as they allow a learner to visualize the spatial relationships anatomical structures have with each other, leading to an increase in a learner's germane load that is thought to optimize learning.[26–28] A 3D model can be manipulated in space so that the learner can tangibly see the relationships between different structures and not have to come up with these connections on their own as is necessary with a 2D anatomical image. One randomized control study of medical students learning structural and functional components of the knee joint compared whether use of a 3D printed model (simulation group) was better than using skeletal models (control group).[22] Both groups received a lecture on the locking-unlocking mechanism of the knee joint but the control group only had access to skeletal models while the simulation group used a 3D printed knee model.[22] The students in the simulation group performed better on a content assessment; researchers speculated that the reason for the difference in scores was due to the fact that the simulation group was able to visualize the ligaments and how they moved during knee locking-unlocking while the control group had to spend more time mentally visualizing the spatial relationship of the ligaments based on what they were taught.[22] This study shows that it is possible to decrease the cognitive load of understanding anatomical spatial relationships when using a 3D model because one can more readily visualize structures and associated movements compared to a static model. Another study of the cervical spine compared the use of a flexible 3D printed model to a static model to see which was more successful at teaching students the movements of the spinal column during flexion and extension.[14] There were 10 participants included in this study consisting of neurosurgical residents, nurse practitioners, and physician assistants—in other words, they were practicing clinicians, and not learning anatomy for the first time.[14] The participants were first shown the static 3D model and were asked what position of the cervical spine would cause the spinal canal diameter to decrease.[14] After the participant gave their answer, they would then show the participant a dynamic 3D printed cervical spine model and would then flex and extend the model and ask if they wanted to change their answer.[14] 6 out of the 10 participants changed their answer to the correct one after using the dynamic 3D model.[14] After the study, participants were asked which model they would prefer to learn from and everyone chose the dynamic 3D cervical spine model.[14] The results of this study illustrate that the use of a flexible 3D printed model may be better at teaching students anatomy concepts compared with static 3D printed models due to the ability to visually see what is happening, allowing for more effective learning.

Given the application of 3D printed anatomical models within medical education and healthcare fields, the aim of this study is to evaluate the effectiveness of flexible 3D printed models of the cervical spine and occiput for the education of second year physical therapy students. To our knowledge, there has not been a study that has investigated the utility of 3D printed models in physical therapy education, outside of an anatomy course. Additionally, we sought to assess whether confidence of cervical spine content improved when using dynamic 3D printed models compared to static models.

METHODS

Development of Dynamic 3D Printed Cervical Spine Models

Sterolithography (STL) files of the first five adult cervical vertebrae (C1-C5) and an adult occipital bone were purchased from two online 3D print libraries. Using an online 3D modeling program, the occiput and C1 were modified to have congruent articular surfaces. Three complete sets of models were printed using fused deposition modeling (FDM) and a standard, rigid polylactic acid (PLA) plastic filament (Figure 1). It was decided to print the bones 50% larger for students to manipulate the models more easily, while still maintaining near life-like handling one would encounter in clinical practice. Hook and loop fasteners, foam sheets, and cords were used to simulate structures such as ligaments, intervertebral discs, and the spinal cord, and all parts were loosely fastened using cords or pipe cleaners. The models depicted three different modalities: 1) a model demonstrating up and down glide of the lower cervical spine, 2) a model showing the function of the anterior and posterior longitudinal ligaments (ALL and PLL) with hook and loop strips that could be removed to demonstrate hypermobility, and 3) a model depicting the function of the transverse ligament and how anterior displacement of C1 affects the spinal cord.

Figure 1. One of the 3D-printed cervical spine models. In this view, hook and loop fastener (white) is visible representing the anterior longitudinal ligament.

Student Participants and Educational Context

The 3D printed models were used in a 15-week Summer 2022 term in a musculoskeletal course (PHTH 622 Musculoskeletal Management II) for second-year students (n=22) in an entry-level Doctor of Physical Therapy program at a small liberal arts college in the northeastern United States. The program runs for 36 months, incorporating didactic and clinical curricula. Musculoskeletal Management I content covers the assessment and treatment of patients across the lifespan with pathologies of the extremities, while the Musculoskeletal Management II course involves pathologies of the spine.

Musculoskeletal Management II is offered at the midpoint of the program—roughly one-and-a-half years into the three-year program. Prior to the Musculoskeletal Management II course, students completed coursework in the basic sciences, as well as a movement science, clinical skills, and research methods sequence, and clinical neuroscience, therapeutic exercise, neurological management, and diagnosing imaging courses. Their gross anatomy course, taught in the first trimester of their first year (Spring 2021), was a 15-week course taught in a hybrid format due to COVID-19; lectures were virtual, and the lab component included in-person whole body cadaveric dissection, but with smaller group sizes and staggered dissections due to state health requirements for reduced capacity in the lab. Additionally, all students successfully completed an 8-week clinical rotation prior to the Musculoskeletal Management II course, and may have been an acute inpatient setting, an outpatient orthopedic setting, or another setting entirely.

Data Collection

On the first day of Musculoskeletal Management II, a pre-test on the cervical spine and informed consent to participate in the study was distributed. The pre-test included 10 multiple-choice questions that measured content knowledge, some that tested baseline knowledge of cervical spine anatomy and other questions that were on the arthrokinematics to be taught in the course. Example questions and their answer choices are found in Table 1. Four additional questions asked students to rate their confidence on a Likert scale explaining or performing a particular cervical spine movement (Not Confident At All = 1, Extremely Confident = 5), and palpating bony landmarks. The pre-test and informed consent were administered on Qualtrics, and students were aware that participation in the study was voluntary. The study was approved by the Marist College Institutional Review Board (#S22-031).

Table 1. Examples of content knowledge questions.

Question Stem	Answer Choices
The flexion rotation test of the cervical spine tests for what?	a) OA (occiput-atlas) dysfunction b) Cervicogenic headache c) Dens fracture d) Sternocleidomastoid muscle length
Which of the following ligaments prevents excessive upper cervical rotation and side bending?	a) Anterior longitudinal ligament b) Transverse ligament c) Alar ligament d) Ligamentum flavum
With lower cervical spine flexion, what arthrokinematics occur at the facets a given vertebral level?	a) Anterior and superior translation b) Anterior and inferior translation c) Posterior and superior translation d) Posterior and inferior translation

During the first two weeks of the course, students were instructed about the cervical spine as it relates to musculoskeletal management in physical therapy practice. All students received the same lecture content in person, with upper cervical spine content first, followed by the lower cervical spine one week later. After lecture content was presented, students participated in lab where they could manipulate models and practice on peer partners. The class was evenly divided into two groups: one that used static, inflexible anatomical models (static model group) that are commercially available, and the other group utilized the flexible, dynamic 3D printed models described with materials to simulate ligaments, spinal cord, and intervertebral discs (dynamic model group). Additionally, the dynamic model group had access to accompanying instructional videos demonstrating use of the models. In these videos, the authors advised users to treat the models with care and explained how the hook-and-loop fasteners functioned as the ALL, PLL, and transverse ligaments and rolled foam simulated the spinal cord. No additional instruction was given in the videos that was not given already a part of the lecture content. Students in the static and dynamic groups had similar abilities, as measured by their grades in the anatomy and movement science courses and no significant differences were found.

Immediately following the respective lab sessions, participants took a post-test on the cervical spine to measure their content knowledge. The post-test consisted of the same multiple choice and confidence questions about the cervical spine given in the pre-test and was administered on Qualtrics. Post-tests were given on two different days, corresponding with when content on the upper and lower cervical spine was presented and labs with model manipulation took place.

Data Analysis

Descriptive statistics of the pre-test and post-test scores were calculated. For the pre- and post-test scores measuring content knowledge, a paired samples t-test was used to determine if there was a difference in pre- and post-test scores among all participants. An independent samples t-test determined whether there was a difference in scores depending on whether participants had access to the dynamic models. Since the upper and lower cervical spine were taught on two different days, additional t-tests determined whether the cervical region and the respective models used had any effects; the upper cervical data were normally distributed and an independent samples t-test was used, while the lower cervical data were not normally distributed, necessitating the use of a non-parametric Mann-Whitney U test.

Descriptive statistics of the confidence levels were also calculated, and independent samples t-tests used to compare means. A Shapiro-Wilk test determined that the lower cervical confidence data from post-test 2 were not normally distributed, and a Mann Whitney U-test was used to calculate the post-test confidence levels between the dynamic and static model groups. Data were analyzed and figures made using GraphPad Prism version 9.4 for Windows.[29]

RESULTS

Content results

Twenty-one students agreed to participate in the study (95.5% participation rate), with 10 participants in the dynamic model group and 11 participants in the static model group. Means and standard deviations of the pre- and post-test scores are shown in Table 2, with the scores reported as percent correct. A paired samples t-test demonstrates that there was a significant difference between pre-test and post-test scores ($t=4.2$, $df=20$, $p=0.00$). There were no significant differences in the post-test scores for the dynamic and static model groups ($t=.66$, $df=19$, $p=0.52$, Figure 2). There were no significant differences in the post-test scores for the dynamic and static model groups when separating the questions into upper and lower cervical spine content assessed on different days. An independent sample t-test showed no significant differences when assessing content of the upper cervical spine using models (t=1.04, df=19, p=0.3, Figure 3). Similarly, the Mann Whitney U test revealed no significant differences when accessing content of the lower cervical spine using the provided models (p=0.81, Figure 4).

Table 2. Descriptive statistics (mean and standard deviation) as percent correct of the pre-test and post-test scores (10 questions total), post-test 1 on upper cervical content (6 questions), and post-test 2 on lower cervical content (4 questions)

Group	Pre-test Total Score	Post-test Total Score	Post-test 1 (Upper cervical content)	Post-test 2 (Lower cervical content)
Dynamic (n=10)	60 (20.55)	74 (15.06)	76.60 (13.89)	77.50 (18.45)
Static (n=11)	51.82 (14.71)	70 (12.65)	69.73 (16.25)	77.00 (19.36)

Figure 2. Post-test Total Cervical Content Knowledge

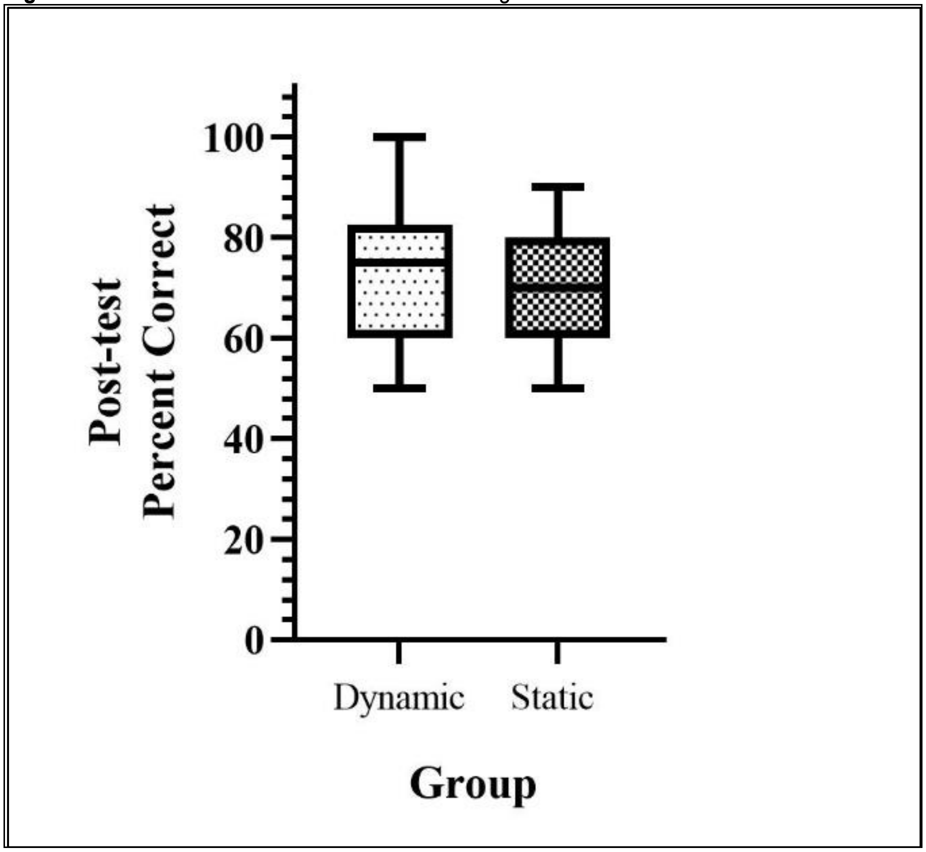


Figure 3. Upper Cervical Post-test Content Knowledge

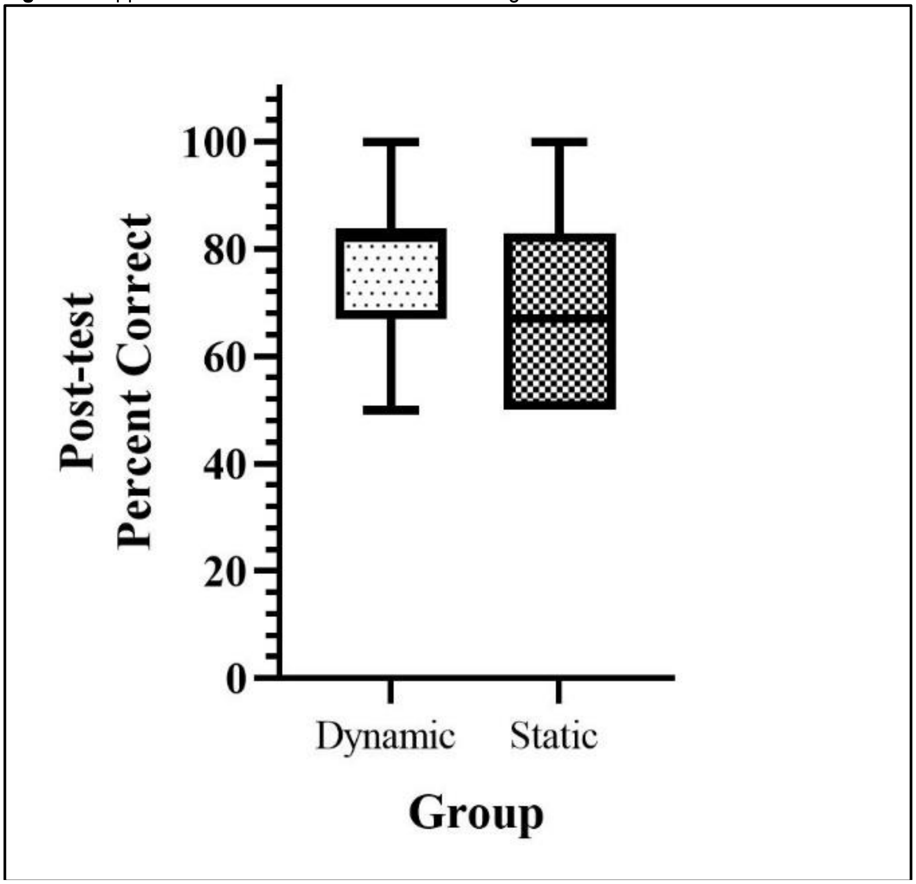
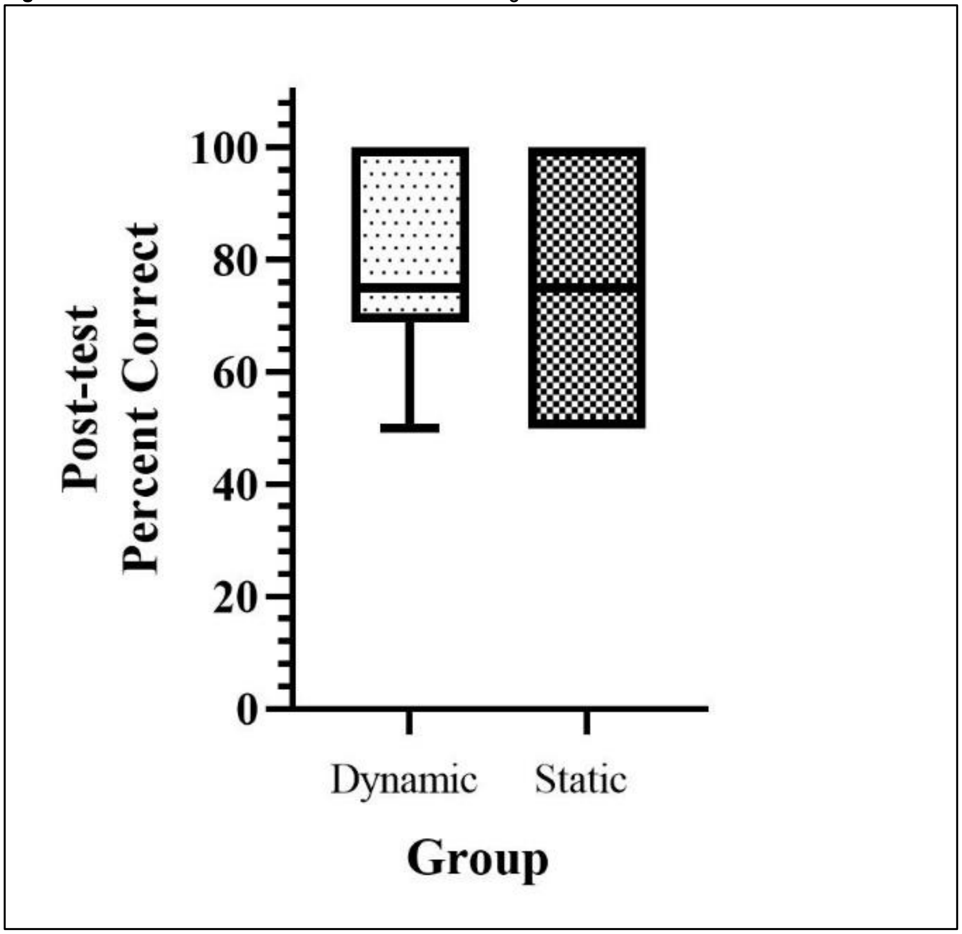


Figure 4. Lower Cervical Post-test Content Knowledge



Confidence results

Descriptive statistics (mean and standard deviation) of the confidence results are presented in Table 3. Comparisons of the post-test confidence levels revealed no difference in confidence with the cervical spine and/or its arthrokinematics in the dynamic model group compared to the static group for any of the confidence items.

Table 3. Descriptive statistics (mean and standard deviation) of the Likert confidence scores by group, and p-values of post-test confidence results. Not Confident At All = 1, A Little Confident = 2, Somewhat Confident = 3, Confident = 4, Extremely Confident = 5

Item	Dynamic Pre-test Confidence	Static Pre-test Confidence	Dynamic Post-test Confidence	Static Post-test Confidence	p-value
1. Confidence explaining cervical spine related dysfunction, i.e., opening and closing restriction to a peer	1.50 (.85)	1.18 (.40)	3.60 (.97)	3.46 (.93)	.5539
2. Confidence performing an “upglide” in mid cervical region	1.50 (.85)	1.00 (.00)	3.00 (1.16)	2.55 (1.13)	.3436
3. Confidence performing a “downglide” in mid cervical region	1.30 (.67)	1.00 (.00)	3.00 (1.16)	2.46 (1.13)	.2811

Item	Dynamic Pre-test Confidence	Static Pre-test Confidence	Dynamic Post-test Confidence	Static Post-test Confidence	p-value
4. Confidence in locating vertebral landmarks	3.40 (.70)	2.55 (.93)	4.00 (.94)	3.73 (1.00)	.5510

DISCUSSION

The aim of this study was to determine whether using dynamic, 3D printed models of the cervical spine improved learning effectiveness in a cohort of second-year physical therapy students. Prior studies provided evidence that 3D printed models improved learning efficiency in both undergraduate and medical students.[14,22,27,28,30–32] However, the current study does not replicate prior studies' findings. While there was a slight increase in post-test survey scores among students who used dynamic 3D printed models, it was not a statistically significant difference.

There are multiple factors that may have contributed to these conflicting results. A possible explanation is that the lab sessions during which students interacted with the dynamic models were not structured adequately enough. Students in the dynamic model group were given the same allotted lab time as the static model group to manipulate the models but the amount of time students spent using the models was not tracked; some in the dynamic model group may have handled the models for the entire time while others in this group may not have handled the models at all. While accompanying videos were made available to those in the dynamic model group, whether they were viewed or not was not tracked. It may be necessary to prescribe a length of time for object manipulation in future studies to ensure that models are manipulated sufficiently to measure model effectiveness, or to ask whether the models were used during learning. Additionally, other studies contrast the use of 3D printed models with very different modes of learning: access to cadavers, plastinated specimens, or two-dimensional images, finding higher test scores or greater learning among participants who manipulated 3D printed models.[27,28,32,33] In our study, both groups had access to three-dimensional models – some that were commercially available and others that were 3D printed. Though the 3D printed models had additional materials to simulate anatomical structures (ligaments) that the non-3D printed models lacked, perhaps they were not unique enough to warrant significant differences in learning as measured by post-test scores. The commercially available models used by the static model group are commonly seen in anatomy and physical therapy labs and feature intervertebral discs, spinal cord, spinal nerves, and vertebral arteries. Since some movement is permitted in these models and they are not entirely rigid, perhaps students were able to manipulate the models sufficiently, thereby capturing the same information as those in the dynamic model group—despite their categorization into a "static" model group for the purposes of the study.

Another reason for the results in our study could be that certain anatomical regions are less beneficial when represented as dynamic 3D printed models, and that 3D printing is not effective for all anatomical regions. Studies have found that the utility of 3D printing of anatomical structures is greater for more complex structures in contrast to relatively "simple" regions.[31,34,35] A recent meta-analysis and systematic review suggest that more complex regions like the skull and spine were better understood in three dimensions, while cardiac anatomy was equally understood using 2D methods or 3D printed models.[30] Yet another consideration is the level of knowledge of the study participants. Studies show that the way experts recognize patterns and organize knowledge are distinct from how novices interpret knowledge.[36] While novices take a superficial, linear approach to their formation of connections, experts utilize a rich, interconnected web-like approach to forming relationships.[37] Perhaps the PT student participants in this study were already on a burgeoning-expert level given their experience on one clinical rotation, baseline knowledge of the cervical spine from their gross anatomy course, and continual discussions of the musculoskeletal system and their movements in previous coursework. It may be worthwhile for future studies to evaluate the effectiveness of dynamic 3D printed models among PT students who are novice learners, such as during an anatomy course.

Furthermore, it is worthwhile to consider the type of students involved in this study: physical therapy students, aware of movements and spatial relationships on a whole, given their future careers as movement specialists. Physical therapy students are conditioned to think about the arthrokinematics of joint movements; therefore, it may be useful to examine whether dynamic models are more effective for other healthcare students (medical, physician assistant) for whom musculoskeletal movement is not a central focus as it is for physical therapy students.

Limitations

A limitation of the study is the unknown spatial abilities of the participants. Studies show a positive correlation between visual-spatial abilities and performance in an anatomy course, although there have been some conflicting findings in this regard.[38,39] It is possible that there were students with strong spatial abilities in the static model group, masking potential advantages of the dynamic 3D printed models.

While the sequence of questions and answer choices were modified, the post-test questions were identical to the pre-test questions. This may have led to a repeated testing bias, as students could have recalled the questions asked previously. A long-term retention study was not conducted. While there were no significant differences in the percent of correctly answered questions depending on type of model used, it is possible that the students who manipulated the dynamic 3D printed models retained knowledge of the arthrokinematics more than those who only had access to the static anatomical models. Lastly, this study presents findings with a small sample size from a single physical therapy program in the United States, and other studies are required to assess its universal application.

CONCLUSION

As the inclusion of 3D printing continues to expand in the fields of healthcare and education, educators will continue to discover ways to effectively teach and train students. Although we did not find a significant difference in the use of dynamic 3D printed models, this study did produce positive results, shown by the small improvement in post-test and confidence scores in the twenty-one students that voluntarily chose to participate in this study. Learning was not hindered in the dynamic model group; using a combination of dynamic and static models can complement one another to enrich student learning. Due to the relatively inexpensive costs to print 3D models, future models and materials can be printed for a more tailored educational experience. While decent cervical spine models can be found for purchase online from commercial vendors for approximately $50.00 U.S. Dollars, higher-quality cervical spine models can cost several hundreds of dollars. Meanwhile, a single spool of PLA filament for 3D printing can cost less than $50.00 U.S. Dollars and multiple cervical spine models, with extra filament to spare for other uses. Aside from the upfront cost of the 3D printer itself, the cost effectiveness of 3D printed models cannot be overstated and can permit replicates of 3D printed models for student learning—in some instances allowing students to print their own models for studying at home.[40] Future studies should include larger samples of students for a better indication of the true effect of 3D printed models and the effects of printed materials should be investigated, such as ligaments and nerves using different filaments to represent the structures more accurately within the human body.

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