

The role of a 3D printed model in the teaching of human anatomy: a meta-analysis

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Abstract

Background: Three-dimensional (3D) printing is an emerging technology widely used in medical education. However, its role in the teaching of human anatomy needs further evaluation. This study compared 3D printed models with conventional models to provide a better understanding of their use in the teaching of anatomy.

Methods: PubMed, Embase, EBSCO, SpringerLink, and Nature databases were searched systematically for studies published up to April 2020 in the English language. This study complies with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. In this study, a meta-analysis of continuous and binary data was carried out. Both descriptive and statistical analysis were adopted.

Results: In the teaching of human anatomy, compared with students in the conventional group, those in the 3D printing group showed several advantages in performance testing, time consumption, students' intention, and usefulness. The leave-one-out method further confirmed the stability of the results.

Conclusions: Compared with students in the conventional group, those in the 3D printing group had advantages in answering accuracy and answering time. In the test of anatomical knowledge, the test results of students in the 3D group were not inferior to those in the traditional group. Results of the autopsy test in the 3D group were better than those in the cadaver or 2D group. More students in the 3D printing group were satisfied with their learning compared with students in the conventional group. The results were influenced by the quality of randomized controlled trials. In the framework of abiding by ethics, the application of the 3D printing model in human anatomy teaching is worthy of expectation.

Introduction

Three-dimensional (3D) printing (also known as additive manufacturing) is a process in which a 3D computer model is transformed into a physical object [1]. Through computer control, the "printed materials" are stacked layer by layer, until the physical object matches the blueprint on the computer. Commonly used materials for 3D printing include durable nylon, gypsum, aluminum, textile materials, polylactic acid (PLA) etc. [2, 3]. Three-dimensional printing has a wide range of applications, including applications in space science, technology, and medicine. For example, technology can be used to scan the human body with magnetic resonance imaging and a computerized tomography scan. It can then replicate human structures with multiple layers of resin [4]. Resin is laid in layers that finally generates solid models.

The applications of 3D printing have expanded gradually. It is a potentially disruptive technology that can improve surgical education and clinical practice [5]. Three-dimensional printing of cerebral arteriovenous malformation models is helpful for preoperative patient consultation, surgical planning, and training [6]. These models can explain the patient's illness, ease the doctor-patient relationship, and improve the patient's confidence in the treatment process. They also provide patients with auxiliary education and

inform them about normal and abnormal body structures, which is conducive to improving doctor-patient relationships [6].

Compared with other tissue engineering scaffolds and rapid prototyping technology, 3D printing has the following advantages: high accuracy, good integration, fast reconstruction, and low cost [7]. It is used to train residents as well as for anatomy education. This technology has shown great potential as an educational tool in areas such as autopsy, plasticization, computer simulation, and anatomical models and images [8]. In recent decades, 3D printing has been employed in the teaching of anatomy to medical students [8]. It is feasible to use this technology to produce high-fidelity models of heart abnormalities. These models impart knowledge about the heart to students and augment their interest in learning [9]. These models can be replicated in large numbers, providing more models for students to use for learning and practicing their skills. One study reported that students found 3D printed models more flexible and durable compared with conventional plastic models [6]. 3D printing has relatively low production costs, generates an accurate anatomical structure, and demonstrates normal or pathological structural changes [10, 11]. The conventional cadaver model anatomy training has several difficulties, including the cost of the cadaver, ethical issues, and the application of formalin preservatives.

The applications of 3D printed models have been investigated in many meta-analyses [12-15]. These meta-analyses were mainly used in the field of surgery. Our study evaluated the application of 3D printed models in medical education. Our research comprised the following processes: (1) A wide range of source data, comprising categorical and continuous variables, were analyzed. (2) Meta-statistical analysis and descriptive analysis were performed. (3) A merger analysis of the effects was performed after deleting individual studies, and the data were visualized. (4) Some studies did not provide the standard deviation (SD) [16, 17], and hence, we estimated it through a formula. In this study, we compared 3D printed models with conventional models to understand the advantages and disadvantages of 3D printed models, and to provide a better understanding of their use in the teaching of anatomy. In our research, conventional teaching models of anatomy include cadavers, plastic products, and two-dimensional (2D) anatomical pictures.

Methods

This study complies with PRISMA (the Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [18].

Study identification and eligibility criteria

We systematically searched PubMed, Embase, EBSCO, SpringerLink, and Nature databases using the following search terms: (“anatomy education” OR “anatomy teaching”) and (“3D printing” OR “three-dimensional printing” OR “3D printed”) and (“student” OR “resident”). We included studies in the English language published up to April 2020. If the full text could not be downloaded, we emailed the respective

authors for the articles. A study was eligible in the meta-analysis if: (1) the anatomy or structure of the human body was identified; (2) a normal or diseased condition was mentioned; (3) a randomized controlled study was conducted; (4) teaching for medical students or junior residents was involved; (5) There were at least 10 participants in the experimental group and the control group. Further (6) there were clear experimental indicators and experimental data. We excluded studies that (1) had no control groups; (2) used animal models; (3) were case reports, letters, comments, review, or other meta-analyses; (4) did not allow extraction of the required data; (5) included republished data; (6) patient education; and (7) was unsuitable for use for other reasons.

Data extraction

For each study, two reviewers (J.H, N.C) independently extracted the first author, publication year, country, the number of experimental and control groups, and a specific comparison between the two groups. Disagreements were resolved through discussion.

Literature quality assessment

We used the GRADEprofiler 3.6 to evaluate the quality of literature included in the study.

The assessment methods included the following items: (1) Experimental design, (2) Risk of bias, (3) Inconsistency, (4) Indirectness, (5) Imprecision, and (6) Publication bias. The quality was assessed by two independent reviewers (J.H, Y.Z).

The result of the quality evaluation is divided into four levels.

High quality: Further research is very unlikely to change our confidence in the estimate of effect.

Moderate quality: Further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate.

Low quality: Further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate.

Very low quality: We are very uncertain about the estimate.

If the quality of literature is evaluated as "High" or "Moderate," we believe that the result will be reliable. If the quality evaluation of the literature is "Low," we believe that the reliability of the results will be low.

Statistical analysis

[Please see the supplementary files to view this section.]

Results

Characteristics of the eligible studies

We searched the relevant databases and read the abstracts and full texts of articles found during this search. Seventeen studies were included in the analysis [8, 16, 17, 21-34].

The publication period of the retrieved literature was between 2015 and 2020. Nine of the seventeen studies were from China, four from the United States, and one each from the United Kingdom, Australia, Japan, and Singapore, respectively. Six studies investigated the use of the models of the nervous system, while five investigated the use of heart models (Table 1). The quality evaluation of most literature studies was high or moderate. Details on the literature quality assessment of the included studies appear in Supplementary Table S1. In all the 17 studies, subjects were divided into groups by randomized controlled grouping. In a few studies, the method of generating random numbers was described in detail. In none of them was the use of any blind method described. In one study, a student dropped out of the test [22]. Since the number of students included in these studies was relatively small, there may have been some bias [16, 22, 25].

Meta-analyses

Post-training tests

1.1 Nervous system model

Six studies compared 3D printed models with conventional nervous system models [17, 21, 26, 28, 31, 34]. There were 198 in the experimental group and 195 in the control group. The results showed a significant difference between the two groups (SMD: 1.27, 95% confidence interval [CI]: 0.82–1.72, $P < 0.05$; Fig. 1). This showed that the performance of the 3D group was better than the conventional group.

1.2 Heart model

Five studies compared 3D printed heart models with conventional heart models. These studies included a total of 100 participants in the 3D printing group and 102 participants in the conventional group [22-25, 29]. Tests were administered after the instructions for using the models or conventional methods had been given. The test score variables were continuous. Due to the different test score standards used in different studies, we used an SMD to merge the means. The results showed no significant difference between the two groups (SMD: 0.37, 95% confidence interval [CI]: – 0.25–0.98, $P > 0.05$; Fig. S1). Therefore, the performance of the 3D group was no better than that of the traditional group.

1.3 Abdominal anatomy

Three papers were included in the study [16, 26, 30]. The results showed that there was a significant difference between the two groups (SMD: 2.01, 95% confidence interval [CI]: 0.55–3.46, $P < 0.05$; Fig. S2). The results showed that the test result of the 3D group was better than that of the control group.

1.4 3D vs cadaver

Four studies compared 3D printed models with cadaver specimens [17, 22, 27, 34]. There were 153 in the experimental group and 149 in the cadaver specimen group. The results showed a significant difference between the two groups (SMD: 0.69, 95% confidence interval [CI]: 0.27–0.99, $P < 0.05$; Fig. 2) (i.e., the performance of the 3D group was better than the cadaver specimen group).

1.5 3D vs 2D

Ten studies compared 3D printed models with 2D pictures [16,21, 23, 24, 26, 28, 29,30,31,33]. There were 379 3D printed models in the experimental group and 378 2D pictures in the control group. The results showed a significant difference between the two groups (SMD: 1.05, 95% confidence interval [CI]: 0.64–1.64, $P < 0.05$; Fig. S3) (i.e., the performance of the 3D group was better than the 2D group).

Answering time

Three studies compared the differences in the answering time between the 3D printing groups and conventional groups [21,25,26]. The random effects model suggested a statistical significance (SMD: –0.61, 95% CI: –0.98 to –0.24, $P < 0.05$; Supplementary Fig. S4). This also suggested that the answering time in the 3D printing groups was shorter compared to the conventional groups.

Usefulness

Three studies compared 3D printed models to conventional models regarding utility [16, 21, 32]. The random effects models suggested a statistical significance (RR = 2.29, 95% CI: 1.22–4.27, $P < 0.05$, Fig. 3). This suggested that the instruction for 3D printing was more useful compared to the instruction for conventional models.

4. Satisfaction

Six studies described the level of satisfaction in the 3D printing and conventional groups [16, 23, 25, 26] [33,34]. Results from five studies indicated that students in the 3D printing group were more satisfied compared to students in the conventional group. Only one article reported that there was no statistical difference in satisfaction between the students in the 3D printing group and those in the conventional group (Supplementary Table S2).

5. Accuracy

Two studies investigated the answering accuracy in the 3D printing and conventional groups [32, 35]. The two studies are descriptive and do not incorporate data. These studies found that answering accuracy in the 3D printing group was better compared to the conventional group (Supplementary Table S3).

6. Sensitivity analysis

Regarding studies about the nervous system, each time a study was deleted and the rest of the data were combined, the P-values were less than 0.05 (Fig. 4), which suggested that the result was stable and reliable. Similarly, while comparing 3D models with cadavers, we omitted one study at a time, and the pooled estimates were calculated in both the 3D printing and conventional groups (Fig. 5). Each time a study was ignored, the pooled estimates were found to be < 0.05 , which suggested that the result was stable and reliable as well.

7. Test for publication bias

In the funnel plots of the 3D printing model and the conventional model of performance testing (nervous system, Fig. 6), both Egger and Begg's tests showed a P-value of > 0.05 , indicating an even and symmetrical distribution with no publication bias. However, the integrated study of 3D vs 2D shows that $P < 0.05$, suggesting that there may be a publication bias.

Discussion

3D printing has become more popular in medical education in recent years. The 17 studies included in this analysis were published between 2015 and 2020 (Table 1). The results showed that the 3D group was superior to the control group in terms of test scores, accuracy, and students' satisfaction when the literature quality was assessed as of a high or moderate quality (Table S1). The test results of the 3D group were better than those of the cadaver group and 2D group, respectively. In the nervous system model and 3D VS 2D, sensitivity analysis suggested that the results were reliable and stable as well. The

result showed that the heart test scores of the 3D group was not better than that of the control group. The literature quality for this was evaluated as low (Table S1). This suggests that in the heart model, the comparison between the two groups may be less stable. The 3D group was better than the control group in usefulness and test time consumption.

In our study, students in the 3D printing groups took less time to answer questions compared to the conventional groups. Wu [26] reported that compared with a conventional group, students in a 3D printing group spent less time answering questions on the pelvis and spine. However, there was no significant difference in the time spent on answering questions related to the upper and lower limbs between the two groups. Li [21] reported that both male and female students spent less time answering questions on the spine models in a 3D group as compared with a conventional group. The different results of the above research may be due to the variations in students and organs. In general, 3D printing groups took less time to answer questions compared to the conventional groups. However, the quality evaluation of the literature is low for this, indicating that the result may not be very stable (Table S1).

Three studies compared 3D printed models with conventional models regarding utility [16, 21, 32], and the random effects model suggested a statistical significance. In terms of usefulness, 3D printed models were found to be more useful compared with conventional models. However, the quality evaluation of the literature for this is low as well (Table S1). Six studies investigated the satisfaction of students in the 3D printing and conventional groups with their learning [16, 23, 25, 26][33,34]. five of these studies showed that the students' satisfaction in the 3D group was better than the conventional group. Only one article mentioned that there was no statistical difference between the two groups. These results indicate that there was more satisfaction among students in the 3D printing groups than among students in the conventional groups (Supplementary Table S2). 3D printing is embraced by students and shows the vitality of new exciting technology. Two studies have investigated the accuracy in answering questions among students in 3D printing groups and conventional groups [32, 35]. Students in the 3D printing groups showed more accuracy in answering questions compared with students in the conventional groups (Supplementary Table). Similar to the post-training test, high accuracy in answering questions represents high test scores.

The visual funnel diagram was tested for symmetry and was found to be symmetrical (Fig. 6). By loading the "meta" package, both Egger and Begg's tests showed a P-value of > 0.05 , indicating the absence of a publication bias.

In the past, for a medical student, the primary learning object was often a real human body. Some of the surgical teaching and research departments in hospitals have anatomical maps displayed to help students learn. Today, some departments teach students how to learn about the human anatomy through 3D computer graphics. 3D printing has the advantages of high accuracy, good integration, fast reconstruction, and low cost. Technology has gradually entered the medical classroom.

3D printing is widely used not only in medical education but also in the field of surgery [36]. These models are also used in surgical oncology, plastic surgery, and dental surgery and are included in the

guides. In addition to educating students and surgeons, studies have highlighted the important role of 3D printing in patient education to improve patient consent [37, 38]. Diment [13] used a descriptive-analytical method to analyze the application of 3D printing models in clinical fields and proposed that 3D models have effective applications. Bai et al. [12] reported in their meta-analysis that 3D print-assisted surgery was better than a conventional surgery in terms of the operation time, blood loss, and good outcome. Compared with a conventional group, a 3D printing group showed a shorter operation time, less intraoperative blood loss, and faster healing time in patients with tibial plateau fractures, suggesting that 3D printing technology-based treatment was appropriate for tibial plateau fractures [15]. Benjamin [39] used descriptive statistical methods to report the role of 3D printed models in surgical education. The author concluded that 3D printing technology has a wide range of potential applications in surgical education and training. Although the field is still relatively new, some studies have shown that education that employs 3D printing can replace or supplement conventional education [39].

3D printed models also have some shortcomings. If students only have access to “scaled” models, it could lead to a lack of understanding of real size and relation to other anatomical components [27]. The accuracy of 3D printed models remains a challenge and they have yet to completely replace human structures [40]. The costs associated with various materials and equipment are also a problem. Moreover, the ethical issues regarding 3D printed models should not be ignored. Careful 3D printing in the anatomy room is correct. The research on 3D printing of the foregut, organ, and archived fetal materials using a donated body or 3D files on the Internet, is of ethical significance [41]. Without the permission of the donor, 3D printing of the body may lead to a lack of “reasonable” informed consent, which is ethically questionable. At worst, if the models are sold for a profit, it could be interpreted as illegal [42]. However, despite potential cost constraints, the prices of 3D printing equipment, materials, and software have been declining [39, 43] and more educational models of 3D printing are becoming learning tools for students [44]. Donating body parts of corpses can be copied cheaply. Providing resources for anatomy education and anatomy schools in poor areas is now possible at a low cost. Hence, we must abide by the ethics when using a 3D printing anatomical model. Therefore, in a good ethical situation, we hope that 3D printing models can not only play a role in surgery and communication, but also in anatomy classes.

Limitations

Most of the papers did not specifically describe the procedures of randomization, such as the method of generating random numbers. It was not suggested whether to adopt blind research. Furthermore, most of the studies were heterogeneous. The possible reasons for this heterogeneity could be the difference in the overall quality of students in different countries, the quality of teachers, the contents and objectives of teaching, the contents of questionnaires, etc. The sample sizes in most of the studies were small as well.

Conclusions

In teaching the human body using 3D printed models, the test results will not be inferior to that of the conventional teaching group. Compared with the cadaver or 2D group, the 3D group has some advantages in test scores. Students in the 3D printing group showed better performance in answering accuracy and usefulness. Most of the students in the 3D printing group were more satisfied with their learning than those in the conventional group. The reliability of the results may be affected by the poor design quality of the randomized controlled trials, the difficulty of the test papers, the background knowledge of students and teachers, etc. In general, in a good ethical situation, the application of a 3D printing model in human anatomy is worthy of expectation and exploration.

Declarations

Abbreviations

3D: Three-dimensional;

SD: standard deviation;

RR : relative risk;

SMD : standardized mean difference.

Ethics approval and consent to participate

We received approval from the ethical committee of Shandong First Medical University & Shandong Academy of Medical Sciences for conducting this research (ethics approval No: 202026). All the authors of this article are aware of the content.

Competing interest

The authors declare no competing interests.

Availability of data and materials

All data and material are available in the manuscript.

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Authors' contributions

J.Z., conceived and designed the study. Z.Y., J.H, N.C., and Z.S, processed the data. Z.Y., W.T., and D.A., performed statistical analysis. Z.Y., completed the article writing. All authors have read and approved the final manuscript.

Consent for publication

Not applicable

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Table

Table 1. Basic characteristics of the 17 included studies

Study	Year	Region	3D vs conventional	Organ	Observe
Li	2015	China	21 vs 22 (female, CT); 19 vs 18 (male, CT)	Spine	Usefulness, answering time
Lim	2016	Australia	16 vs 18 (cadaveric materials)	Heart	Test results
Chen	2017	China	26 vs 27 (cadaver materials)	Skull	Test results
Jones	2017	United States	17 vs 19(2D images)	Vascular rings and slings	Test results
Loke	2017	United States	18 vs 17 (2D images)	Anatomy of congenital heart disease	Knowledge acquisition, satisfaction, test results
Smith	2017	United Kingdom	66 vs 61 (cadaver materials)	Heart, lung	Test results
Wang	2017	China	17 vs 17 (plastic cardiac model)	Heart	Satisfaction, answering time, choice tendency
Cai	2018	Singapore	17 vs 18 (2D images)	Knee joint	Accuracy
Huang	2018	China	47 vs 47 (physical model)	Acetabulum	Objective tests, usefulness, accuracy, choice tendency
Lin	2018	China	22 vs 20 (atlas)	Head	Test results
Su	2018	China	32 vs 31 (CT)	Heart	Test results
Wu	2018	China	45 vs 45 (CT)	Spine, pelvis, upper limb, lower limb	Satisfaction, answering time, test results
Bangeas	2019	United States	10 vs 10 (2D images)	Colon, rectum	Satisfaction, usefulness, choice tendency, test results
Hojo	2019	Japan	51 vs 51 (textbook group/2D images)	Pelvis	Test results

Yi	2019	China	20 vs 20 (2D images)	Head	Test results
Chen	2020	China	23 vs 24 (2D images)	Gastrocolic Trunk	Test results, satisfaction
Jordan	2020	United States	45 vs 43 (cadaver materials)	Skull	Test results, satisfaction

Figures

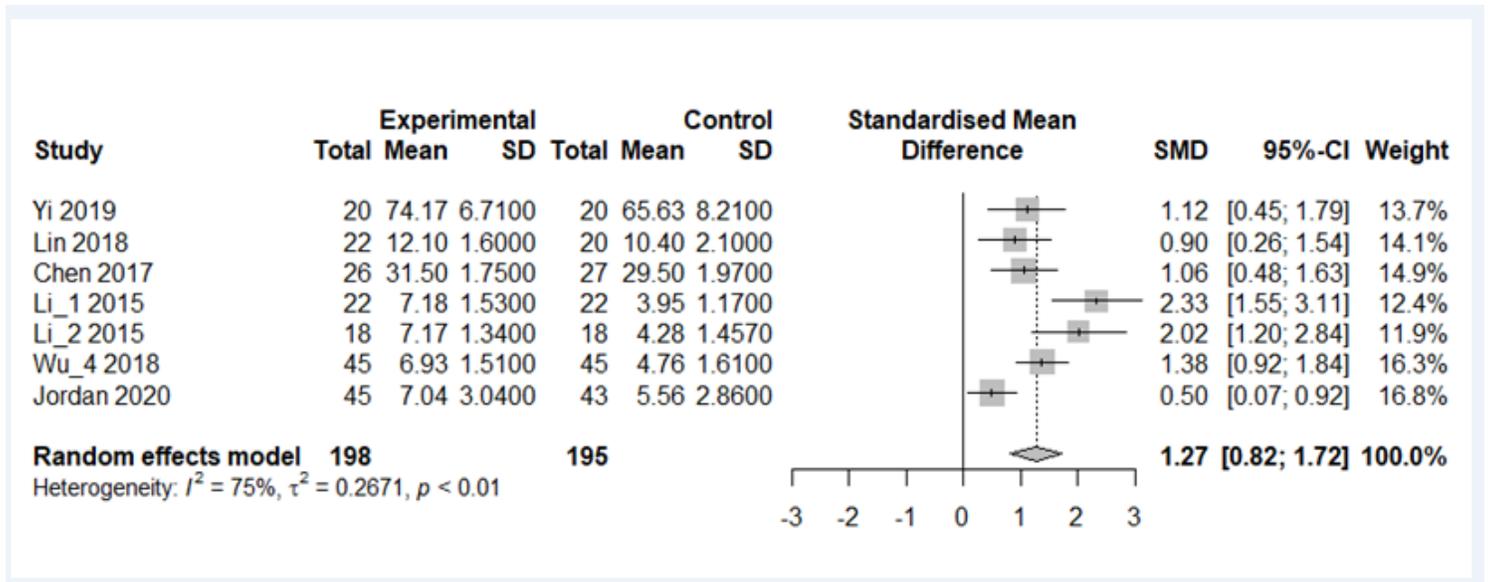


Figure 1

Comparison of test results of the experimental and the control groups for nervous system models. A meta-analysis of continuous data.

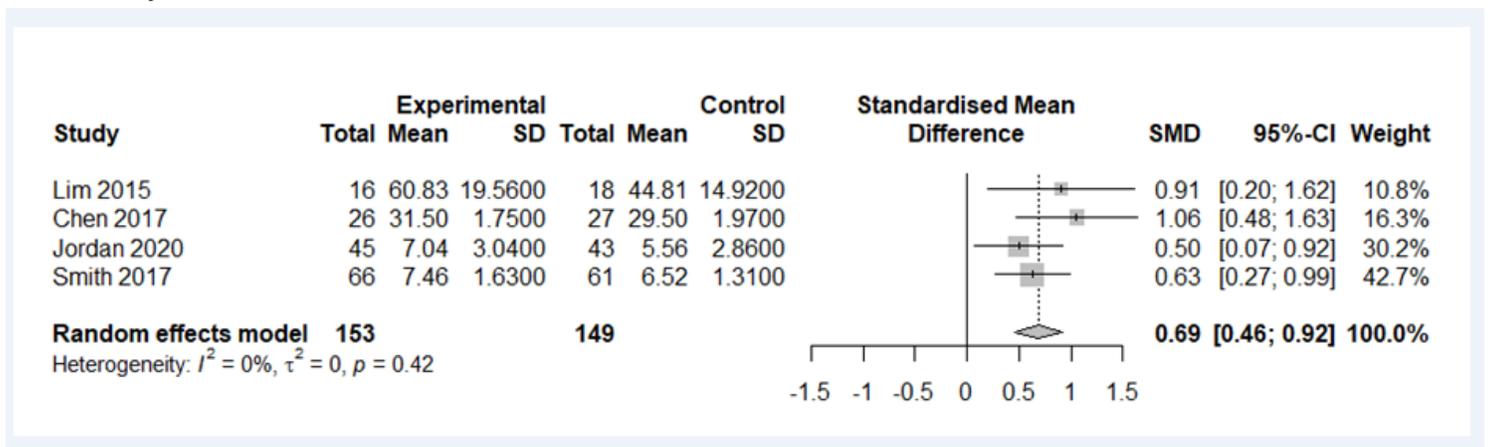


Figure 2

Comparison of test results of the 3D and cadaver groups. A meta-analysis of continuous data.

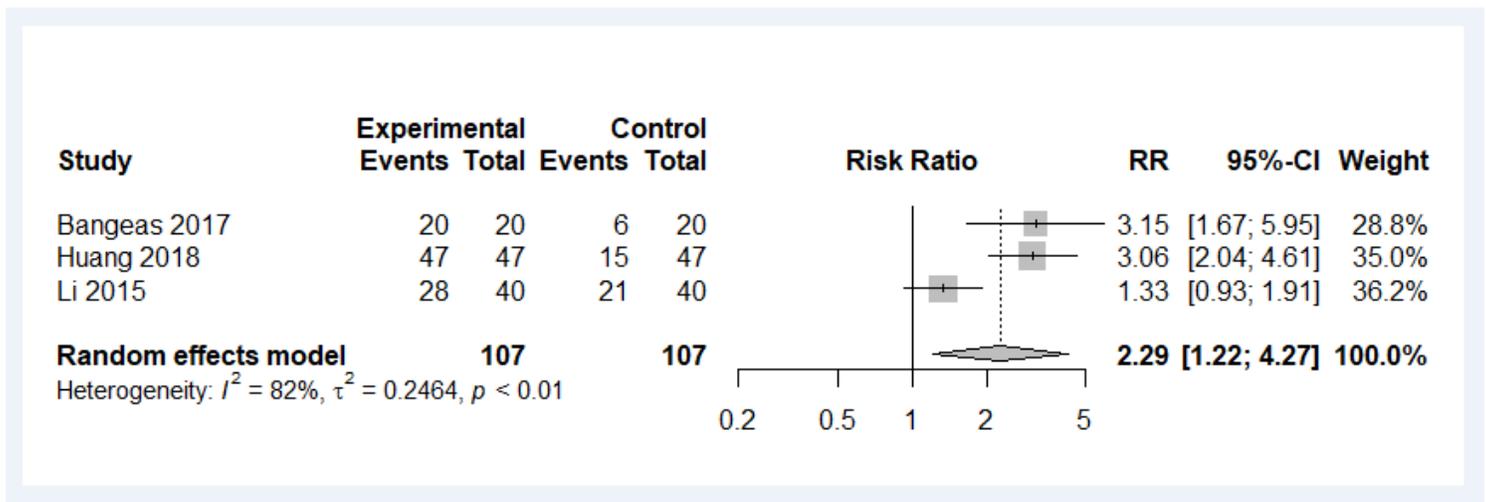


Figure 3

Compared 3D printed models with conventional models concerning a utility. A meta-analysis of binary data.

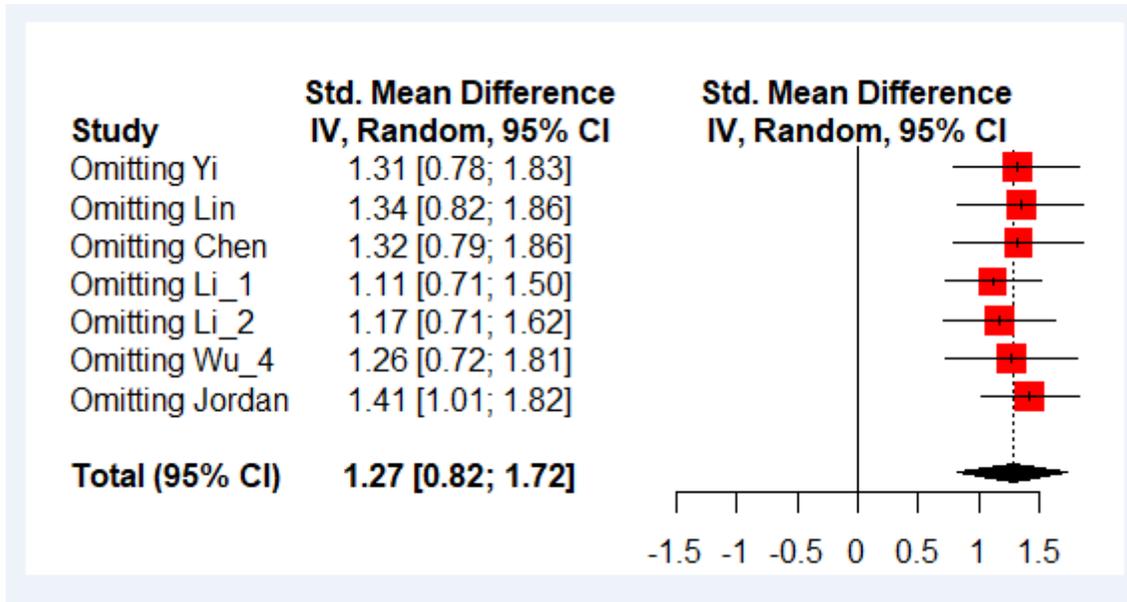


Figure 4

Sensitivity analysis of meta-analysis of test results of nervous system models in the experimental and control groups using the leave-one-out method. Li_1 and Li_2 were obtained from the same source literature. The data from Li_1 was obtained from the females, while that of Li_2 was obtained from the males. Wu_1 through Wu_4 were obtained from the same literature. Wu_1 data were obtained from the upper limbs, and Wu_2 data were obtained from the lower limbs. Wu_3 data was obtained from the pelvis, and Wu_4 data was obtained from the spine.

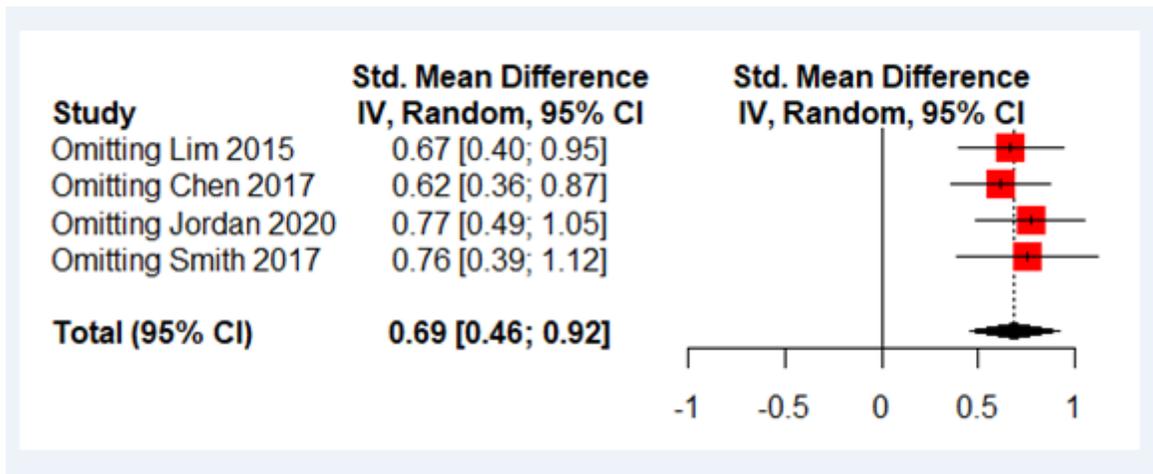


Figure 5

Sensitivity analysis of meta-analysis of test results in 3D and cadaver groups using the leave-one-out method.

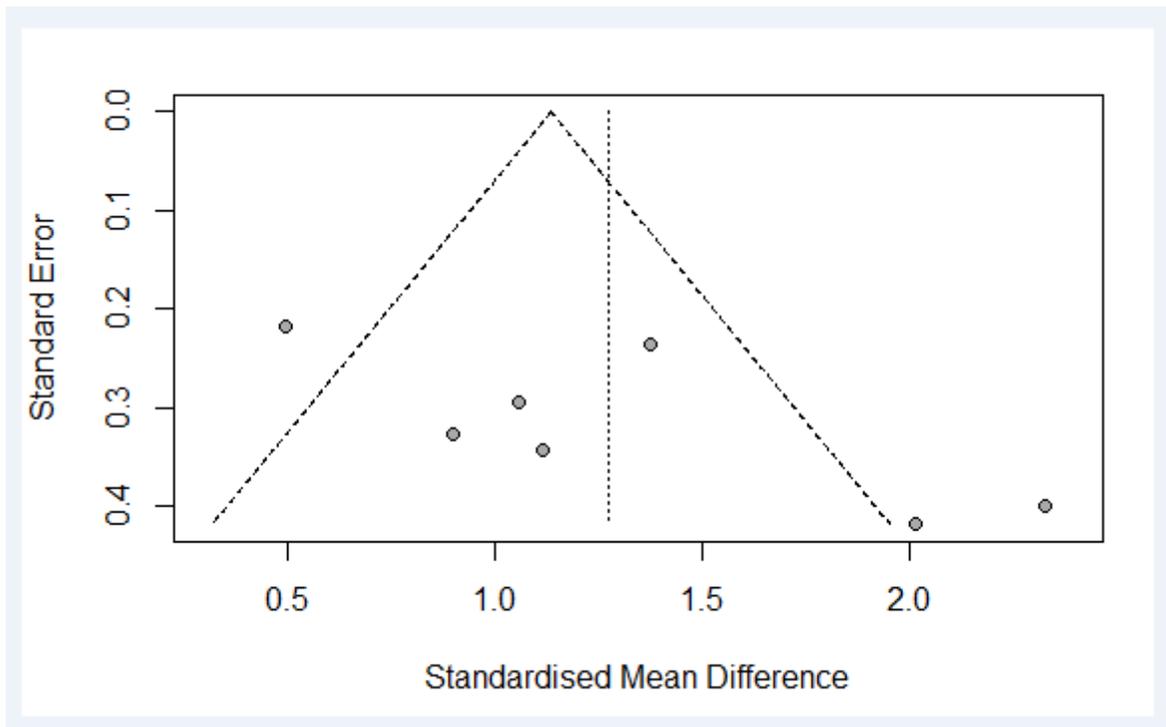


Figure 6

Funnel plot of standardized mean difference of the test results of nervous system models in the experimental and control groups.

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