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The role of 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 that is widely used in medical education. This study compared 3D printed models with conventional models to provide a better understanding of the use of 3D printed models in the teaching of anatomy. Methods PubMed, Embase, EBSCO, SpringerLink, and Nature databases were searched systematically for studies published up to December 2019 in the English language. This study complies with PRISMA guidelines. In this study, a meta-analysis of continuous data and binary data was carried out. Both descriptive analysis and statistical analysis were adopted. Results Compared with students in the conventional group, students 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, students in the 3D printing group had advantages in answering accuracy and answering time. For most anatomical sites, the 3D group has certain advantages in terms of test scores and time consumption. More students in the 3D printing group were satisfied with their learning compared with students in the conventional group. The role of the 3D printing model in human anatomy education is worth looking forward to.

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 nylon glass fiber, durable nylon material, gypsum material, aluminum material, titanium alloy, stainless steel, silver plating, gold plating, and rubber materials. Three-dimensional printing has a wide range of applications, including applications in space science and technology and medicine. For example, the technology can be used to scan the human body with magnetic resonance imaging and computerized tomography and then replicate human structures with multiple layers of a resin material[2]. The material is laid in layers that finally generates solid models.

The applications of 3D printing have expanded gradually. 3D printing is a potentially disruptive technology that can improve surgical education and clinical practice[3]. 3D printing of cerebral arteriovenous malformations models is helpful for preoperative patient consultation, surgical planning, and training[4]. 3D printed models can also explain the patient's illness, ease the doctor-patient relationship, and improve the patient's confidence in the treatment process. These models also provide patients with auxiliary education and inform them about normal and abnormal body structures, which is conducive to improving doctor-patient relationships[4].

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[5]. It is used not only to train residents but also for anatomy education. The technology has shown great prospects as an educational tool in such areas as the autopsy, plasticization, computer simulation, and anatomical models and images[6]. In recent decades, 3D printing has been employed in the teaching of anatomy to medical students[6]. It is feasible to use 3D printing technology to produce high-fidelity models of heart abnormalities. These models impart knowledge about the heart to students and augment their interest in learning[7]. 3D printed models can be replicated in large amounts, which provides more models for students to use to learn and practice their skills. One study reported that students found 3D printed models to be more flexible and durable compared with conventional plastic models[4]. 3D printing has relatively low production costs, generates an accurate anatomical structure, and demonstrates normal or pathological structural changes[8, 9]. There are, however, some shortcomings in the use of 3D printed models in the teaching of anatomy. Conventional cadaver model anatomy training has several difficulties as well, 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[10–13]. 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 has the following characteristics: (1) a wide range of source data, which consisted of categorical and continuous variables, were analyzed; (2) meta-statistical analysis and descriptive analysis were performed; (3) merger analysis of the effects was performed after deleting the individual studies and the data were visualized. (4) Some studies did not provide the standard deviation (SD)[14, 15], and we estimate it through the 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 the use of 3D printed models 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[16].

Study identification and eligibility criteria

We systematically searched PubMed, Embase, EBSCO, SpringerLink, and Nature databases using the following search terms: “anatomy education” and (“3D printing” OR “three-dimensional printing” OR “3D printed”) and (“student” OR “resident”). We included studies in the English language published up to December 2019. 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 trial or quasi-experimental 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 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.

Assessing risk of bias

This study employed the risk of bias assessment method recommended by Cochrane. The assessment methods included the following items: (1) random sequence generation, (2) allocation concealment, (3) blinding of participants and personnel, (4) blinding of outcome assessment, (5) incomplete outcome data, (6) selective reporting, and (7) other bias. The risk assessment was based on the following criteria: "low risk" indicated a low risk of bias, "high risk" indicated a high risk of bias, and "unclear" indicated uncertain information. The higher an included study's risk of bias, the lower the quality. The risk of bias was assessed by two independent reviewers (HJ and ZY).

Statistical analysis

This study included a meta-analysis of categorical and continuous variables. For the categorical data, we used R version 3.5 (http://www.r-project.org/) to calculate relative risk (RR) values and to compare the results. For continuous data, due to different scoring standards, a standardized mean difference (SMD) was used to compare the results. For the conjoint analysis of continuous variables, we needed to know the mean ($\overline{X}$) and SD of the experimental and control groups. The specific $\overline{X}$ and SD values were not provided in the two papers[14, 15], so we calculated them using published formulas as followed[17].

Q1: First quartile

m: Median

Q3: Third quartile

n: Number of samples

$$\overline{X} \approx \begin{cases} \frac{(Q1+Q3+2m)}{4}, & n \le 25 \\ m, & n > 25 \end{cases}$$

$$SD \approx \begin{cases} \frac{1}{\sqrt{12}} * \left[(Q3-Q1)^2 + \frac{(Q1+Q3-2m)^2}{4}\right]^{\frac{1}{2}}, n \le 15 \\ \frac{Q3-Q1}{4}, \ 15 < n \le 70 \\ \frac{Q3-Q1}{6}, \ n > 70 \end{cases}$$

Heterogeneity was tested with the chi-square test. The P-value in the chi-square test was less than 0.10, which indicates that there was heterogeneity in the studies, so we used the random effect model to merge the data; otherwise, we used the fixed effect model.

Publication bias was evaluated using a funnel plot if a sufficient number of studies (n > = 5) were included. The funnel chart was examined by Egger's and Begg's methods. It indicated that there was publication bias if p < 0.05. Stability of the data was assessed through sensitivity analysis. We performed a sensitivity analysis by deleting a study, combining effects, and comparing results if a sufficient number of studies (n > = 4) were included. In the above study, we used R language by loading "meta" packages (https://cran.r-project.org/web/packages/meta/index.html). The experimental group represented the 3D printed model group, and the control group represented the conventional group. The teaching models of the traditional group include real autopsies, plastic models, or two-dimensional images. A P-value < 0.05 was considered statistically significant.

Results

Characteristics of the eligible studies

We searched the relevant databases and read the abstracts and full texts of articles found during the search. Fifteen studies were included in the analysis [6, 14, 15, 18–29].

The publication period of the retrieved literature was between 2015 and 2019. Eight of the fifteen studies were from China, three from the United States, one from the United Kingdom, one from Australia, one from Japan, and one from Singapore. Four studies investigated the use of heart models, and five investigated the use of models of the nervous system (Table 1). Details on the risk of bias assessment of the included studies appear in Supplementary Table S1. All 15 studies divided their subjects into groups by randomized controlled grouping. A few studies described their method of generating random numbers in detail. None of the studies described the use of any blind method. In one study, one student dropped out of the test[19]. The numbers of students included in the studies were relatively small, and as a result, there may have been some bias [14, 19, 22]. Further, some studies were conducted in different regions, which may have caused some bias.

Table 1
Basic Characteristics of the 12 Included Studies

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

Meta-analyses

1. Post-training tests

1.1 Nervous system model

Five studies compared 3D printed models with conventional nervous system models [15, 18, 23, 25, 28]. There were 152 in the experimental group and 153 in the control group. There was heterogeneity between studies ($P < 0.10$, $I^2 = 58\%$), we used a random-effects model for the pooled analysis. The results showed there was a significant difference between the two groups (SMD: 1.41, 95% confidence interval [CI]: 1.01–1.82, $P < 0.05$; Fig. 1). This showed that the performance of the 3D group was better than the traditional group.

1.2 Heart model

Four studies compared 3D printed heart models with conventional heart models. These studies included a total of 83 participants in 3D printing groups and 83 participants in conventional groups [19, 20, 22, 26]. Tests were administered after instruction using the models or conventional methods had been given. The test score variables were continuous. Because of the different test score standards used in different studies, we used an SMD to merge the means. Because the studies were significantly heterogeneous ($P < 0.10$, $I^2 = 77\%$), we used a random-effects model for the pooled analysis. The results showed no significant difference between the two groups (SMD: 0.18, 95% confidence interval [CI]: – 0.48–0.84, $P > 0.05$; Fig. 2). Therefore, the performance of the 3D group was no better than that of the traditional group.

1.3 Motion system

Two studies compared 3D printed models with conventional motion system models [24, 26]. There were 156 in the experimental group and 151 in the control group. There was no heterogeneity between studies ($P > 0.10$, $I^2 = 11\%$), we used a fixed-effects model for the pooled analysis. The results showed there was a significant difference between the two groups (SMD: 0.33, 95% confidence interval [CI]: 0.11–0.56, $P < 0.05$; Fig S1). This showed that the performance of the 3D group was better than the traditional group as well.

1.4 Abdominal anatomy

Three papers were included in the study [14, 23, 27]. The test of the heterogeneity had a statistical significance ($P < 0.10$, $I^2 = 89\%$). 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.

2. Answering time

Three studies compared the differences in answering time between the 3D printing groups and conventional groups. The studies were significantly heterogeneous ($P < 0.10$, $I^2 = 73\%$). The random-effects model suggested a statistical significance (SMD: – 0.61, 95% CI: – 0.98 to – 0.24, $P < 0.05$;

Supplementary Fig S3). This also suggested that answering times in the 3D printing groups were shorter compared to the conventional groups.

3. Usefulness

Three studies compared 3D printed models to conventional models regarding utility [14, 18, 29]. The studies were significantly heterogeneous ($P < 0.10$, $I^2 = 80\%$). The random-effects models suggested statistical significance (RR = 2.28, 95% CI: 1.24–4.22, $P < 0.05$; Supplementary Fig. 3). This suggested that instruction employing 3D printing was more useful compared to conventional instruction.

4. Satisfaction

Four studies described the level of satisfaction in the 3D printing and conventional groups [14, 20, 22, 23]. Results from three studies indicated that students in the 3D printing groups were more satisfied compared to students in the conventional groups. Only one article reported that there was no statistical difference in satisfaction between students in the 3D printing group and those in the conventional group (Supplementary Table 2).

5. Accuracy

Two studies investigated the answering accuracy in the 3D printing and conventional groups [29, 30]. These studies found that answering accuracy in the 3D printing group was better compared to the conventional group (Supplementary Table 3).

6. Sensitivity analysis

In the study of the nervous system, each time one study was deleted and the rest of the data were combined, the P-value were less than 0.05 (Fig. 4), which suggested that the result was stable and reliable. Similarly, in the heart model, 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 estimate 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 (Fig. 6), both Egger's and Begg's tests showed a P-value of > 0.05, which indicated an even and symmetrical distribution and no publication bias.

Discussion

The 15 studies included in this analysis were published between 2015 and 2019 (Table 1). 3D printing has become more and more popular in medical education in recent years. Out of the 15 included studies, 8 were from China. Due to the uneven sources of literature, there might be regional bias.

In the past, for the 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 hanging to help students learn. Today, some departments teach students how to learn human anatomy through 3D computer graphics. 3D printing has the advantages of high accuracy, good integration, fast reconstruction, and low cost. The technology has gradually entered the medical classroom.

After 1–2 class training, our research showed that there was no significant difference in test scores between the 3D printed heart group and the traditional group in the random-effects model ($p > 0.05$). Sensitivity analysis indicated that the result was reliable. However, in the nervous system model, motor system and abdominal anatomical model, the performance of the 3D group was better than the traditional group. In the nervous system model, sensitivity analysis suggested that the result was reliable and stable as well. The reasons for the above differences might be as follows: (1). The number of literature included in the study was relatively small; (2). The content of the test was different, the degree of difficulty was different, and the crowd was different. In our study, students in the 3D printing groups took less time to answer questions ($P < 0.05$), compared to the conventional groups. Wu[23] reported that compared with a conventional group, students in a 3D printing group spent less time answering questions on the pelvis and spine, although there was no significant difference in the time spent on the questions related to the upper and lower limbs between the two groups. Li[18] reported that both male and female students spent less time answering spine models in a 3D group compared with a conventional group. The different results of the above research may be due to variations in the students and organs. In general, 3D printing groups took less time to answer questions compared with conventional groups. This result may be because 3D printed models are easy for students to learn from and easily arouse students' interests. As can be seen from the above, for most anatomical sites, the 3D group has certain advantages in terms of test scores and time consumption.

Three studies compared 3D printed models with conventional models regarding utility, [14, 18, 29] and random effects models suggested statistical significance ($P < 0.05$). In terms of usefulness, 3D printed models were found to be more useful compared with the conventional model. Four studies investigated the satisfaction of students in the 3D printing and conventional groups with their learning [14, 20, 22, 23]. Three 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 the students in the conventional groups (Supplementary Table 1). 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 [29, 30]. Students in the 3D printing groups showed more accuracy in answering questions compared with students in the conventional groups (Supplementary Table 2). 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 (https://cran.r-project.org/web/packages/meta/), both Egger's and Begg's tests showed a P-value > 0.05, indicating the absence of publication bias.

3D printing is widely used not only in medical education but also in the field of surgery [31]. 3D printing models are also used in surgical oncology, plastic surgery, and dental surgery and are included in guides. In addition to educating students and surgeons, studies have highlighted the important role of 3D printing in patient education to improve patient consent [32, 33]. Diment [11] used a descriptive-analytical method to analyze the application of 3D printing models in the clinical fields and proposed that 3D models have effective applications. Bai et al. [10] reported, in their meta-analysis, that 3D print-assisted surgery was better than conventional surgery in terms of the operation time, blood loss, and good outcome. Compared with a conventional group, a 3D printing group showed 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 [13]. Benjamin [34] 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 [34].

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 [24]. The accuracy of 3D printed models remains a challenge and they have yet to completely replace human structures [35]. The costs associated with various materials and equipment are also a problem. Moreover, the ethical issues regarding 3D printed models should not be ignored. However, despite potential cost constraints, the prices of 3D printing equipment, materials, and software have been declining, [34, 36] and more and more educational models of 3D printing are becoming learning tools for students [37]. Therefore, we hope that 3D printing models will play a role not only in surgery and communication but also in the anatomy classroom.

Limitations

Because most of the 15 papers included in this study were from China, there were potential sources of bias. 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 are as follows: the overall quality of the students in different countries was different, the quality of teachers was different, the contents and objectives of teaching were different, the contents of questionnaires were different, etc. The sample sizes in most of the studies were small.

Conclusions

For most anatomical sites, the 3D group has certain advantages in terms of test scores and time consumption compared to the conventional group. Students in 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 role of the 3D printing model in anatomy education is worth looking forward t

Abbreviations

3D:Three-dimensional;

SD: standard deviation;

RR : relative risk;

SMD : standardized mean difference.

Declarations

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. All the authors of this article are aware of the content.

Conflict of Interests

The authors declare no competing interests.

Availability of data and materials

All data and material are available in the manuscript.

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Notes on contributors

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.

Consent for publication

Not applicable

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Figures

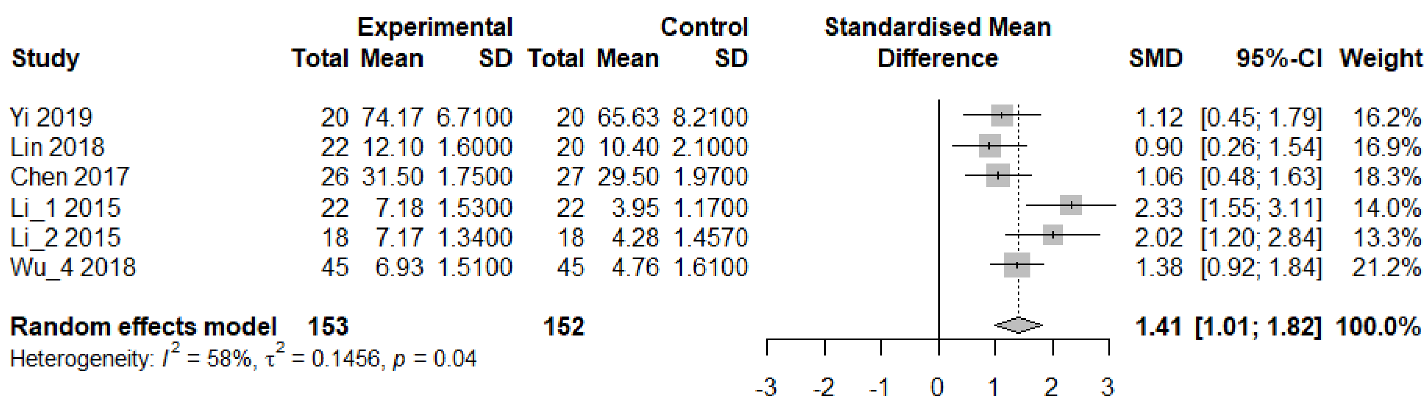

Figure 1

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

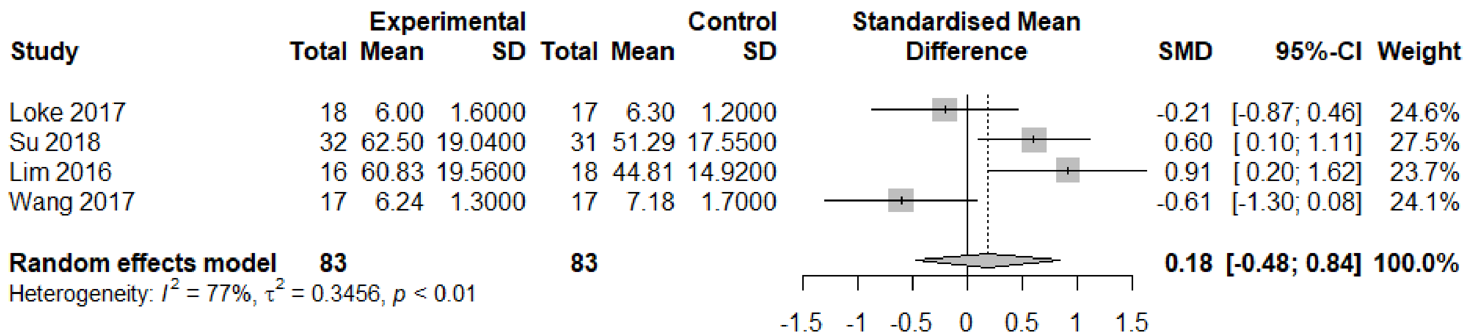

Figure 2

Comparison of test results of the experimental and control groups for heart models.

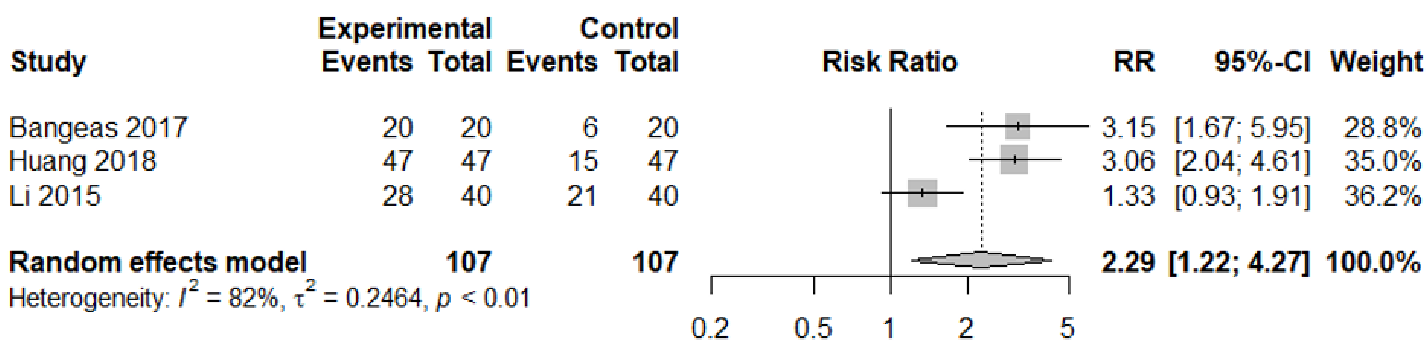

Figure 3

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

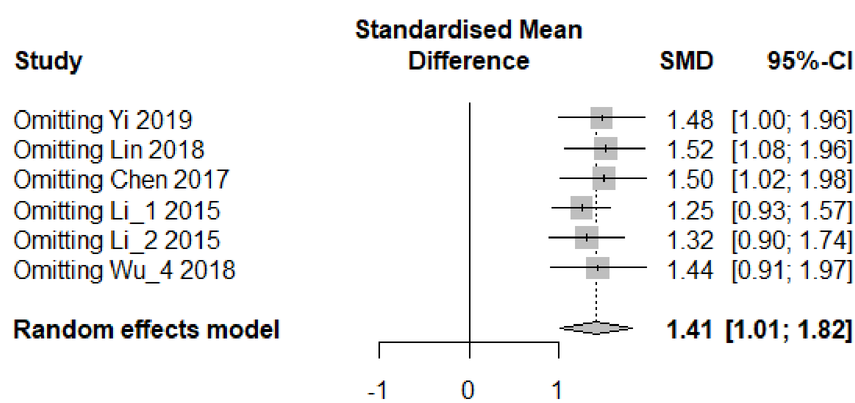

Figure 4

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.

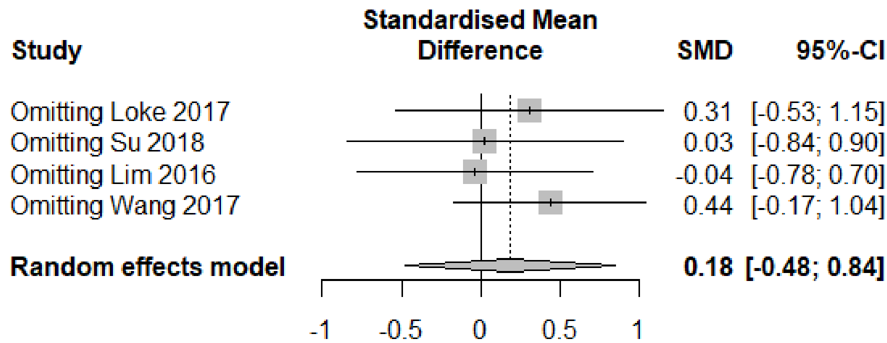

Figure 5

Sensitivity analysis of meta-analysis of test results of heart models in the experimental and control groups using the leave-one-out method.

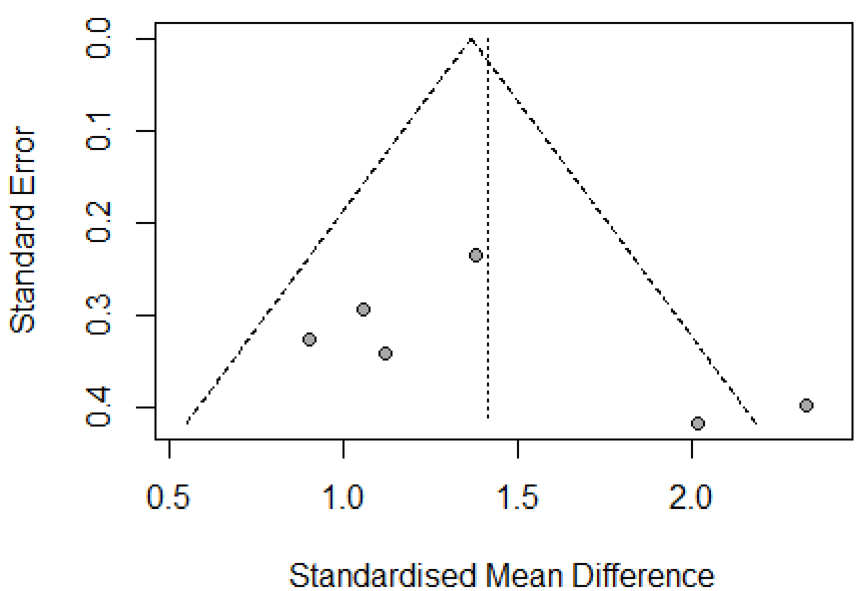

Figure 6

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

Supplementary Files

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- PRISMA2009checklist.doc