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Students' perception of three-dimensionally printed teeth in endodontic training

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Abstract

Introduction: In endodontic education, there is a need for thorough training prior to students embarking on clinical treatment. The aim of this study was to use three-dimensional printing technology to create a new model and to compare its suitability for training purposes with resin blocks and extracted teeth.

Materials and Methods: Multi-jet-modelling (MJM) produced the 3D model replicating a common difficulty in root-canal morphology. An evaluation study comprising 88 students was run in the sixth semester (summer 2018 and winter 2018/2019). A new questionnaire assessed students' perception of training models and educational environment. Welch's *t*-test analysed significant differences.

Results: The most pronounced differences between models were noted when rating material hardness, radiopacity, root-canal configuration and suitability for practising. Students estimated their learning outcome as greater with 3D-printed teeth compared to resin blocks. Three-dimensionally printed teeth received significantly lower ratings with regard to enthusiasm, the learning of fine motor skills and spatial awareness, when compared to human teeth ($p \leq .001$). However, 3D-printed teeth were appreciated for additional benefits, such as their cleanliness, availability and standardisation of training opportunities with complex root-canal configurations.

Conclusion: Students preferred extracted human teeth to 3D-printed teeth with respect to their physical characteristics and training experience. However, educational advantages may compensate for the shortcomings. The new questionnaire proved both adequate and accurate to assess the models and educational environment in endodontic training. The new 3D-printed teeth enhanced the learning opportunities.

KEYWORDS
3D-printed tooth, dental education, endodontics, root-canal treatment, teaching materials, three-dimensional printing

1 | INTRODUCTION

The ability to perform root-canal treatment is a core competence trained early on during preclinical dental education and has major impacts on the subsequent training of clinical treatment with real patients. Medical simulations with models support the acquisition of practical skills before their employment in real-life scenarios. Simulation, coupled with three-dimensional printing technology, has become particularly prominent in dentistry over the last few years.[1] Whole teeth including the pulp cavity can be designed individually and are, therefore, predestined to use in high-fidelity simulation models, including realistic haptic features.[2,3] Most recently, Höhne et al. designed teeth with realistic carious lesions and pulp cavities and used 3D printing to create tooth models, in which different layers of enamel and dentine could be distinguished for crown preparation.[4,5] Hanisch et al. even developed surgical models for endodontic surgery (apicoectomy) based on real patient data.[1] For undergraduate endodontic education, Hanafi et al. recently introduced a modular 3D-printed training model, in which both extracted human teeth and artificial tooth replicas can be embedded.[6] Factors appearing to drive the acceptance of simulation models in dental education are the need to provide a safe training environment, standardisation in training opportunities for the whole cohort and a seamless transition from preclinical training into clinic for students through the use of models mimicking real patient conditions.[7] Furthermore, efficient learning with unrestricted resources, objective and reproducible feedback, unlimited training hours and enhanced cost-effectiveness for teaching are all associated with dental simulation training.[8] Last but not least, the models should also promote student enthusiasm to be educated.[9] Not surprisingly, a variety of models have been developed to help students train endodontic skills, as root-canal treatment is both complex and technically demanding particularly with regard to the length and homogeneity of the root-canal fillings.[10] For many years, common models for educational purposes ranged from simple root canals in clear epoxy resin blocks to extracted human teeth. However, extracted teeth do have a number of disadvantages, such as the risk of infection from organic material still present, the limited availability and the anatomic variability, making standardised training for students difficult.[8,11] These days, rapid advances in 3D-printing technology have enabled the fabrication of artificial teeth that mimic the anatomic and mechanical properties of extracted human teeth. These do not bear the risk of infection, are available in small or even large quantities and allow for validated assessment through their uniformity, a characteristic easily modified to offer anatomic challenges, and thus specific training scenarios.[4,5,12]

Thus, there is growing evidence that current 3D-printing technology, such as multi-jet modelling (MJM) is particularly suitable to simulate the distinct anatomic morphology of narrow root canals. In contrast to the stereolithographic printers that use a liquid bed of photopolymer cured after each cross section, MJM printers work more like an inkjet printer by depositing the photopolymer layer by layer.[13,14] This technique allows printing at a higher resolution.[15] Kröger et al. was one of the first groups to use earlier 3D-printing technology to create innovative models in endodontic education.[3] The workgroup of Robberecht developed a specific ceramic shaping technique using 3D printing to produce a template and slipcast of a root-canal mould to reproduce canal systems with the desired shape.[16] Reymus et al. digitised extracted teeth with cone beam computed tomography (CBCT) and produced highly accurate replicas using stereolithographic printing.[17] In this study, a MJM printer was employed to create an individualised 3D training model for root-canal treatment. The development of the 3D-printed tooth was based on scanned human teeth and included some explicit modifications for two different root canals. Thus, this model is considered as the first to have been generated with such a fine anatomic structure.

The focus of this study was to investigate student acceptance and the learning benefits of such an individualised 3D-printed tooth model in a preclinical course (sixth semester). A further objective was to implement a questionnaire and evaluate the results to compare how students perceive and experience working with the new root-canal model with the current methods of traditionally extracted teeth and resin blocks. Data analysis also served the purpose of inspecting the content and construct validity of this questionnaire.

2 | MATERIALS AND METHODS

2.1 | Ethics and data protection

The local ethics review board evaluated the proposal for this study (Ethics ID 269/18). It was their assessment that the study did not qualify as biomedical or epidemiological research and the data were generated anonymously using the EvaSys® (Electric Paper Evaluations Systeme GmbH) platform. The data were collected with the consent of the dentistry students. No personal information other than gender, age and educational status were gathered from all participants. Neither the decision to participate or not, nor the results of the questionnaire had any consequence on a student's academic progress. Student ratings could not be linked to individual course grades or academic performance. Data were processed and stored in accordance with current data protection laws.

2.2 | Data collection

The study took place in the sixth semester during the practical course of conservative dentistry and periodontology employing dental simulation models in phantom heads. During this preclinical phase of the 5-year degree course, undergraduate dental students train cavity preparation, filling and root-canal treatment. A member of the departmental teaching staff led the course with a team of assistant dentists supervised by a dental consultant. Students were requested to evaluate their training experience with the three root-canal models investigated. A pilot study, in which the questionnaire was developed and tested, took place in the winter term of 2017/2018. For measurement and data generation, the subsequent validation study was run in the summer term of 2018 and in the winter term 2018/2019.

2.3 | Questionnaire development

The questionnaire was developed with a team of experts comprising a professor of medical education, a professor of conservative dentistry, two psychologists and an assistant dentist of conservative dentistry (Table 1). The questionnaire for the validation study was adapted following the results of the pilot study. Some items were eliminated and response options for the semantic differential were collapsed to three steps.

The final instrument included personal data on age, gender, non-academic apprenticeship as dental technician and difficulties obtaining extracted teeth. It included 40 items in six different categories: evaluation of the didactic quality of the course, characteristics in comparison of three pairs (3D-printed tooth vs. extracted tooth, resin block vs. extracted tooth and 3D-printed tooth vs. resin block), estimate of learning outcome and effects of training. At the end, students were able to enter free-text comments.

Item-response options comprised a 5-point Likert scale, a 3-point semantic differential and open questions. Forced-response options were gradually scored on a 5-point Likert scale with numerical values for measurement: "strongly disagree" (1), "disagree" (2), "neutral" (3), "agree" (4) to "strongly agree" (5) and "no specification (0)". The semantic differential employed three steps: the response option on the left or negative pole of the scale, the middle as identical and the right or positive pole. Open questions were summarised. The questionnaire was created using EvaSys®, the survey was run paper based.

2.4 | Practical course for root-canal preparation and fabrication of the 3D-printed teeth

The practical course started by using the resin blocks (Flex Master exercise block, V040245, VDW, Munich, Germany and root-canal study model without clinical crown, S1-U4, J. Morita, Tokyo, Japan). The first task was to prepare the artificial root canal manually using hand files. Thereafter, students trained root-canal preparations mechanically using two types of torque-controlled motor (Silver Reciproc, VDW and X-Smart Plus, Dentsply Maillefer) and reciprocating files. Subsequently, for the first time during their degree course, students practised on extracted teeth (two incisors, two premolars and two molars; already root-filled teeth, teeth with highly curved roots or large carious lesions were excluded a priori). Students performed manual and mechanical root-canal preparation on each tooth type. Finally, root-canal preparation was practised on a specially designed replica (Figure 1). The educational steps comprised treatment planning, including initial X-rays, preparation of the endodontic access cavity, determination of root-canal length, as well as shaping, cleaning and obturation. These treatment steps were the same for all three training models. However, owing to the characteristics, treatment planning and preparation of the endodontic access cavity were not feasible for the resin block and were solely performed on the isolated model. On the contrary, the preparation of the extracted teeth and the 3D-printed teeth was performed on phantom head units. Assistant dentists supervised and verified each step.

The tooth design was based on micro-CT data of an extracted mandibular premolar. The root-canal system was created with open-source 3D-segmentation software (ITK-SNAP, www.itk-snap.org) and modified with open-source 3D-rendering software (Blender, http://www.blender.org) to imitate Vertucci class V root-canal morphology, in which the main canal divides in the middle third of the root into two separate and distinct canals with separate apical foramina.[18] An Objet30 Dental Prime 3D printer was employed using VeroWhitePlus™ material and SUP705™ supporting structure (all from Stratasys), enabling ultrafine printing of the root-canal morphology.[15] In addition to introductory lectures on different root-canal morphologies in general, students were informed about the specific features of the 3D-printed teeth, and received a printout highlighting the root-canal system (Figure 1B).

2.5 | Quantitative and qualitative analysis

Statistical analysis was conducted using IBM SPSS 27.0 (IBM SPSS) and R (R: A language and environment for statistical computing, R Foundation for Statistical Computing). With a mean effect size (Cohen's) of 0.5 and a type II error of 0.95, a sample of 90 students in cross-sectional data was required for sample size calculation. Given the conservatively set type II error rate, a marginally lower sample size is considered statistically uncritical.[19] Descriptive information included item mean (*M*), minimum (Min) and maximum (Max) and standard deviation (SD). Group differences were analysed using Welch's *t*-test.[20]

Free-text comments were analysed thematically, employing an inductive approach. Coding and theme development were driven by the content of the comments.

3 | RESULTS

The study comprised 88 students, of whom 77.72% were female. The average age was 23.45 ± 2.73 (*M* and SD) years and varied between 20 and 31 years. 93.18% of students had no apprenticeship as dental technician. Agreement with item 1.4 (difficulties obtaining extracted human teeth in external dental practices/clinics) was rather high at 3.07 ± 1.23.

The didactic quality of the phantom course was evaluated within the framework of faculty quality assurance measures (Table 2, category 1). Students highly rated the degree of competence of

TABLE 1 Questionnaire developed for the study

Personal data				
1.1 Please select your gender.	male ☐		female ☐	
1.2 Please enter your age	____			
1.3 Did you complete an apprenticeship as dental technician prior to your studying dentistry?	yes ☐		☐ no	
			1 2 3 4 5	0
1.4 I had difficulties obtaining extracted human teeth in external dental practices/clinics.			☐☐☐☐☐	☐
Evaluation of the didactic quality of the course			1 2 3 4 5	0
2.1 The course teaching staff have excellent knowledge of the procedures for root-canal treatment.			☐☐☐☐☐	☐
2.2 The teaching staff was able to provide me with valuable assistance.			☐☐☐☐☐	☐
2.3 I was well supervised by the teaching staff.			☐☐☐☐☐	☐
2.4 The course was well organised.			☐☐☐☐☐	☐
2.5 I had enough opportunities to practise.			☐☐☐☐☐	☐
Comparison of characteristics between a 3D-printed tooth and an extracted tooth				
Compared to an extracted human tooth, the 3D-printed tooth is/has in my opinion...		identical		
3.1	harder	☐ ☐ ☐	softer	
3.2	more radiopaque	☐ ☐ ☐	less radiopaque	
3.3	ample root canals	☐ ☐ ☐	tight root canals	
3.4	more suitable for practice	☐ ☐ ☐	less suitable for practice	
3.5	fairer for exams	☐ ☐ ☐	less fair for exams	
3.6	better suited to practical exams	☐ ☐ ☐	less suited to practical exams	
3.7	easier in terms of handling	☐ ☐ ☐	more complex in terms of handling	
The 3D-printed tooth has/gives...				
3.8	a comprehensible root-canal morphology	☐ ☐ ☐	no comprehensible root-canal morphology	
3.9	a realistic tactile impression when preparing	☐ ☐ ☐	no realistic tactile impression when preparing	
Comparison of characteristics between a resin block and an extracted tooth				
Compared to an extracted human tooth, the resin block is/has in my opinion...		identical		
4.1	harder	☐ ☐ ☐	softer	
4.2	more radiopaque	☐ ☐ ☐	less radiopaque	
4.3	ample root canals	☐ ☐ ☐	tight root canals	
4.4	more suitable for practice	☐ ☐ ☐	less suitable for practice	
4.5	fairer for exams	☐ ☐ ☐	less fair for exams	
4.6	better suited to practical exams	☐ ☐ ☐	less suited to practical exams	
4.7	easier in terms of handling	☐ ☐ ☐	more complex in terms of handling	
The resin block has/gives...				
4.8	a comprehensible root-canal morphology	☐ ☐ ☐	no comprehensible root-canal morphology	
4.9	a realistic tactile impression when preparing	☐ ☐ ☐	no realistic tactile impression when preparing	
Comparison of characteristics between a 3D-printed tooth and a resin block				
Compared to a resin block, the 3D-printed tooth is/has in my opinion...		identical		
5.1	harder	☐ ☐ ☐	softer	
5.2	more radiopaque	☐ ☐ ☐	less radiopaque	
5.3	ample root canals	☐ ☐ ☐	tight root canals	
5.4	more suitable for practice	☐ ☐ ☐	less suitable for practice	
5.5	fairer for exams	☐ ☐ ☐	less fair for exams	
5.6	better suited to practical exams	☐ ☐ ☐	less suited to practical exams	
5.7	easier in terms of handling	☐ ☐ ☐	more complex in terms of handling	
Estimated learning outcome			1 2 3 4 5	0
6.1 Compared to the work with extracted human teeth, my estimated learning success was much greater after working with 3D-printed teeth.			☐☐☐☐☐	☐
6.2 Compared to the work with resin blocks, my estimated learning success was much greater after working with 3D-printed teeth.			☐☐☐☐☐	☐
6.3 Practical training with extracted human teeth is very similar compared to 3D-printed teeth.			☐☐☐☐☐	☐
6.4 After the course, I feel confident in treating root canals.			☐☐☐☐☐	☐
Effects of training			1 2 3 4 5	0
7.1 Extracted human teeth have generated enthusiasm to learn and master the root-canal treatment.			☐☐☐☐☐	☐
7.2 Extracted human teeth were very helpful to acquire the underlying fine motor skills.			☐☐☐☐☐	☐
7.3 Extracted human teeth facilitated spatial awareness in root-canal treatment.			☐☐☐☐☐	☐
7.4 The 3D-printed tooth generated enthusiasm to learn and master the root-canal treatment.			☐☐☐☐☐	☐
7.5 The 3D-printed tooth was very helpful to acquire the underlying fine motor skills.			☐☐☐☐☐	☐
7.6 The 3D-printed tooth facilitated spatial awareness in root-canal treatment.			☐☐☐☐☐	☐
Free commentaries				
8.1 How can model teeth be improved in future?				
8.2 In your opinion, what are the advantages of extracted human teeth in dental education?				
8.3 In your opinion, what are the advantages of 3D-printed teeth in dental education?				

Note: Rating on the 5-point Likert scale ranged from "strongly disagree" (1), "disagree" (2), "neutral" (3), "agree" (4) to "strongly agree" (5) and "no specification" (0).

the course teaching staff, their assistance in root-canal treatment, as well as their level of supervision. The items "enough training possibilities to practice" and "organization of the course" were assessed only neutrally. The students' overall positive feedback of the

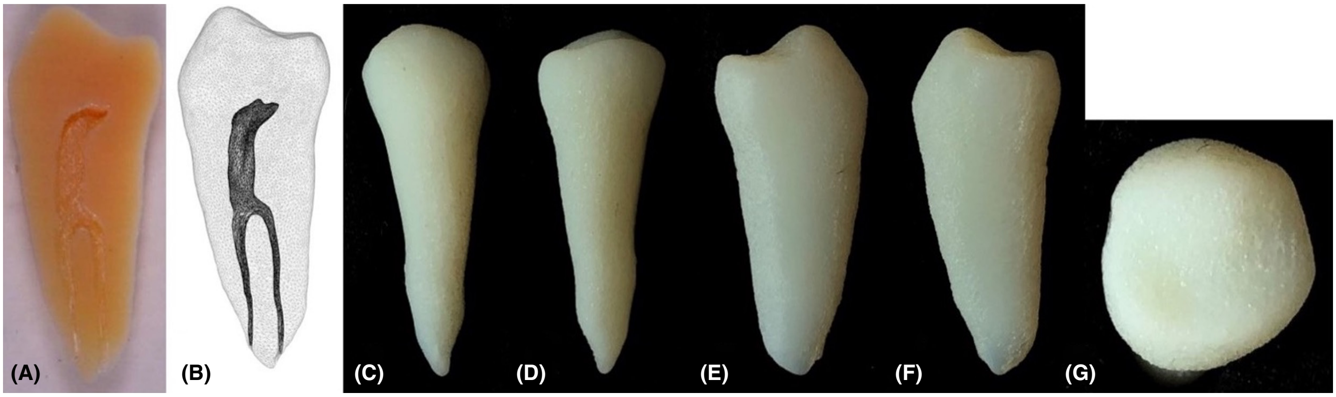

FIGURE 1 Manufactured 3D-printed tooth from different views: cross section with anatomic root-canal morphology in view (A), cross section of detailed root-canal morphology with highlighted pulp (B), frontal (C), lingual (D), mesial (E), distal (F), occlusal (G) aspects

TABLE 2 Descriptive results of students' assessment in the categories didactic quality of the course and estimated learning outcome

Categories	Item	*M* ± SD	Min	Max
1. Evaluation of the didactic quality	2.1 The course teaching staff have excellent knowledge of the procedures for root-canal treatment.	4.20 ± 0.73	2	5
	2.2 The teaching staff was able to provide me with valuable assistance	4.00 ± 1.06	1	5
	2.3 I was well supervised by the teaching staff.	3.94 ± 1.02	1	5
	2.4 The course was well organised.	3.16 ± 0.99	1	5
	2.5 I had enough opportunities to practise.	3.48 ± 1.07	1	5
2. Estimated learning outcome	6.1 Compared to the work with extracted human teeth, my learning success was much greater after working with 3D-printed teeth.	1.98 ± 0.84	1	5
	6.2 Compared to the work with resin blocks, my learning success was much greater after working with 3D-printed teeth.	3.27 ± 1.31	1	5
	6.3 Practical training with extracted human teeth is very similar compared to 3D-printed teeth.	2.51 ± 1.02	1	4
	6.4 After the course, I feel confident in treating root canals.	2.75 ± 0.85	1	5

Note: Rating on the 5-point Likert scale ranged from "strongly disagree" (1), "disagree" (2), "neutral" (3), "agree" (4) to "strongly agree" (5) and "no specification" (0). Data given as item mean (*M*) with standard deviation (SD), minimum (Min) and maximum (Max).

course was a prerequisite for the further, more detailed analysis to compare the different training models.

Students also rated their estimated learning outcome (Table 2, category 2). They did not favour the option of working with the 3D-printed teeth when compared to extracted teeth, but perceived greater benefits from the 3D-printed teeth than from resin blocks. Items 6.3 (similarity of practical training with extracted teeth compared to 3D-printed teeth) and 6.4 (confidence in the treatment of root canals) were also rated averagely.

Figure 2 depicts the characteristics of the training models in more detail. Students assessed the comparison of model pairs on a semantic differential; the indifferent rating (i.e. "models were identical") was represented by the middle response option. Differences between 3D-printed teeth compared to extracted teeth and resin blocks, respectively, were most pronounced when rating material hardness, radiopacity, complexity of the root-canal configuration and suitability for practising. On comparison of the pair 3D-printed teeth versus extracted teeth, students mostly rated towards the right or negative pole, the soft material properties and the low radiopacity being the most prominent items. However, the items "fairer for exams" and "comprehensible root-canal morphology" were rated more positively. The comparison of the resin block with the extracted tooth also displayed these positive aspects. Moreover, students differentiated the resin block as harder material. When comparing the 3D-printed tooth to the resin block, students tended towards more identical ratings, apart from the perceived material hardness.

Students evaluated the effects of training with the 3D-printed tooth and the extracted tooth (Figure 3). The human tooth received higher ratings for the three items "enthusiasm to learn and master

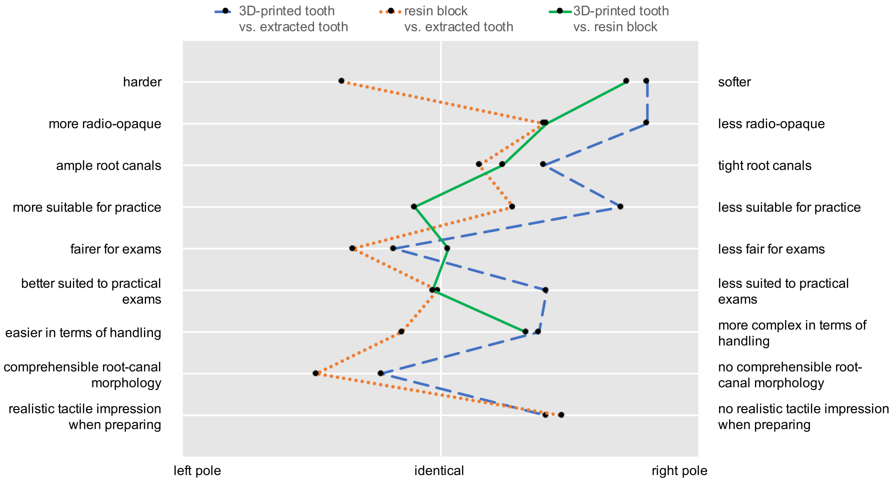

FIGURE 2 Students' assessment of the characteristics of 3D-printed teeth, resin blocks and extracted teeth compared with each other using the semantic differentials as indicated. Rating took place on a 3-point semantic differential. *M* are marked as points. No data were collected for the comparison of both training models (3D-printed tooth and resin block) with regard to comprehensible root-canal morphology as well as tactile impression when preparing as the reference of the extracted tooth was not included

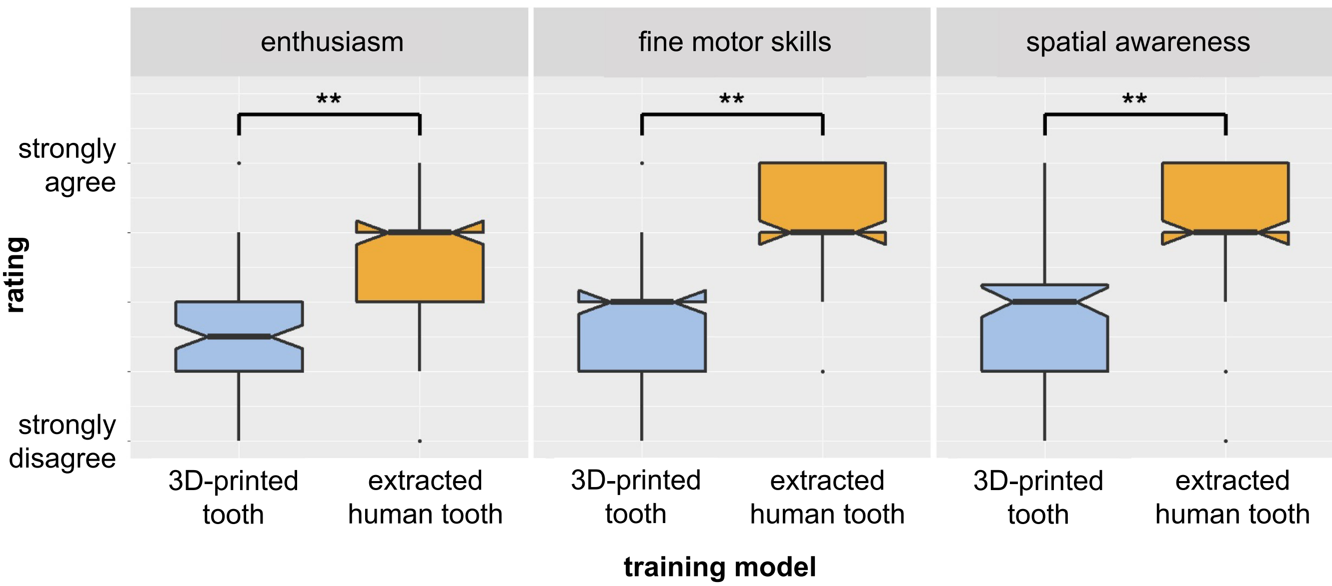

FIGURE 3 Students' assessment of enthusiasm, fine motor skills and spatial awareness of 3D-printed teeth and extracted teeth. Rating on the 5-point Likert scale ranged from "strongly disagree" (1), "disagree" (2), "neutral" (3), "agree" (4) to "strongly agree" (5) and "no specification" (0). The line of the notched box plot indicates the median of the data, whilst the notch represents the 95% confidence interval, the box represents the interquartile range of the 25th to the 75th percentile, at least 50% of data are within the area of the box, the whiskers include 99.3% of the data, outliers are marked as points,[21] $^{**}p \le .001$

root-canal treatment", "acquisition of fine motor skills" and "facilitation of spatial awareness" ($p \le .001$).

The free commentaries reflected the students' suggestions as to how to improve training with 3D-printed teeth in future. One third of the students entered some comment. An increase in radiopacity as well as material hardness were mentioned most frequently. Beyond that, the idea of changes to the colour design of the 3D-printed tooth, especially to delimit the hard enamel as well as the dentin from the pulp, was raised. Furthermore, students requested more time for practice on the 3D-printed teeth and less time with the resin blocks. Some also suggested an alteration in the order of training steps: resin blocks, 3D-printed teeth and finally extracted teeth.

Students frequently mentioned the standardisation of training opportunities as well as the specific training of complex root-canal configurations as major advantages of 3D-printed teeth. The authentic anatomic morphology and opportunity to practise the preparation of endodontic access cavities were also valued. Keeping in mind the difficulties obtaining adequate extracted teeth, students endorsed the training with the 3D-printed tooth to decrease the risk of malpractice incidents prior to their practice on real patients.

4 | DISCUSSION

Advances in technology to produce simulation models for endodontic training are dramatically affecting dental education. Particularly, tooth replicas with realistic endodontic systems based on micro-CT or CBCT data obtained from extracted human teeth and produced by additive manufacturing are considered state of the art for undergraduate endodontic education.[17] This new level of simulation, in addition to previous common models, has major impacts on the layout of training courses and modifies how the teaching of individual steps of complex tasks is performed in dental schools. However, the new innovative models in endodontic education have to be reviewed and compared to the common training models carefully.[7] To date, extracted teeth are considered as the gold standard in preclinical education.[22] The question remains as to what extent 3D-printed models can live up to this standard. Alternatively, if the models prove to be inferior, what are the additional educational advantages associated with the training with 3D-printed teeth, which can compensate for the shortcomings of material properties or anatomic morphology. Consequently, the fairness in obtaining the appropriate material and opportunities to acquire competences, the standardisation of practical examinations and fundamental hygiene aspects finally determine the choice of the didactic method.

Systems to evaluate teaching and course quality in medical and dental education have long been established.[23] Whilst a large number of possible sources of feedback and evaluation (including course documentation, curriculum design processes, teaching committees and students' performance in examinations) exist, the most common and helpful source of input to develop teaching is feedback from participants.[24–26] Indeed, the collection of data from student evaluation surveys is routine practice in most medical or dental schools and a mandatory aspect of quality assurance procedures.[27,28] The primary purpose is to improve the quality of course delivery and to provide direct feedback to teaching staff. Nevertheless, students also provide useful insight into their learning experience mediated by the course material, the utility of training models and the learning environment of simulation.[29,30]

A new questionnaire aimed at measuring the course concept and benefits using three different trainings models, including the newly designed 3D-printed tooth for root-canal preparation, was developed, implemented and validated. This work also closes the research gap as to how to measure students' perception of the training in endodontic education accurately.

4.1 | Practical contribution and validation of the questionnaire

A few questionnaires for the quantifiable evaluation of endodontic education have been published recently. In a study by Nassri et al., professors of endodontics were presented with 14 items to evaluate the anatomic, physical and radiographic features of opaque and transparent resin models for endodontic training.[31] Every single item was rated on a four-step scale in the range of "great" to "poor". The study by Al-Sudani focused on preparation steps as well as on the use of instruments and offered eight items, three response options and one ranking of advantages to rate differences between the artificial plastic and acrylic models and natural teeth.[32] A questionnaire with 11 multiple-choice items was used in a study by Reymus to evaluate the self-made, 3D-printed teeth comparing anatomic features with human teeth, individual treatment steps, properties of the material and advantages in utility.[17] Here, a questionnaire is presented, which not only aims to measure the perceived differences in characteristics among the three models for root-canal preparation, mainly for cleaning and shaping procedures, but also mirrors the students' experience with teaching quality, the estimated learning outcome and the effects of the training. Response options were chosen in the form of a 5-point Likert scale for agreement to items or a 3-point semantic differential for the assessment of the models. Content validity was ensured through the involvement of endodontic and didactic experts to formulate the items as well as guarantee that the questionnaire covered the different facets of the educational environment. As a matter of construct validity, the questionnaire proved capable of measuring differences between the models well (differential validity) and assisted in identifying both advantages and room for improvement.[33]

4.2 | Assessment of the new 3D model and utility for education

In this study, the 3D-printed tooth reproduced a number of features mimicking human teeth. Students highly appreciated its use towards standardisation of the endodontic training by becoming accustomed to a distinct morphologic difficulty. However, the new model was not superior to the extracted teeth with respect to certain physical properties (radiopacity, material hardness), and therefore, received lower ratings for the effects of training on "enthusiasm to learn and master the root-canal treatment", "acquisition of fine motor skills" and the "facilitation of spatial awareness". Not surprisingly, students preferred the 3D-printed tooth to the transparent resin block, which was mainly designed to visualise, and thus to understand the shape of the root canal more easily.[34] Additional differences in the setting of training, such as the lack of all treatment steps and solely preparation outside the phantom head unit, may have also negatively influenced the students' rating. The order of the models and their associated respective educational benefits, namely, resin block first to acquire basic competence, then extracted teeth as the established model for hands-on preclinical training and finally 3D-printed teeth to provide an anatomic challenge, could have led to a still favourable evaluation of the extracted teeth. Nevertheless, students recognised the advantages of 3D-printed teeth as a realistic simulation of clinical treatment and uniformity in assessment.

The results coincide with the findings by the workgroup of Al Sudani, who attested multiple advantages of artificial resin teeth, but denied them being any replacement to natural teeth.[32] Luz et al. also investigated both entities, thereby focusing on the preparation time and perceptions of difficulty, suggesting that neither of the alternative models fulfilled the requirements to replace natural teeth in endodontic teaching.[35] As a matter of fact, the conventional resin block is known for its initial hardness, thus easing the initial preparation of a root canal until the material wears during instrumentation.[16,17] It can, therefore, be considered as a suitable entry-level model despite its drawbacks. The 3D-printed tooth was technically limited with its rather low material hardness, owing to the material required by the MJM printing process, but enabled more complex root-canal configurations. The definite challenge was the second, obliterated deep-branching canal, which was technically more demanding and time consuming to prepare appropriately.[36]

Students suggested improvements, which they stated in the free-text comments. They reflected the hardness of natural tissues and recommended the use of a harder material to create the 3D-printed tooth, a greater radiopacity, as well as better colour differentiation between the enamel, dentine and pulp. Even though a variety of 3D printers and different materials can be used to fabricate tooth replicas, no material or printing approach, to date, seems able to simulate human dentine in every desired aspect.[15] The physical shortcomings of the 3D-printed teeth were also addressed by other workgroups. Reymus et al. employed barium sulphate to increase the radiopacity of the 3D-printed teeth.[17] Höhne et al. added a specific enamel layer for prosthodontic education and the overall rating of students for such teeth was "good".[5] Based on these technical refinements, it would seem feasible at least to integrate such features into the applied new 3D-model. This would allow a model for both endodontic as well as prosthodontic training by combining a complex root-canal morphology with possible treatment pitfalls together with carious lesions or failed crowns.

The question remains as to how the teaching approach and the opportunity to practise in preclinical courses really influence the outcome of root-canal treatment in the clinical environment. Here, it is worth noting that Tchorz was unable to detect any differences in quality dependent on prior training with models when performing root-canal treatments on patients for the first time.[37] To obtain those results, students were split into two groups: one group performed simulated endodontic training on plastic blocks and extracted human teeth, and the second group practised on plastic blocks and artificial resin teeth. This study demonstrates that the best available artificial simulation model compensated practising on human teeth.

Given the positive results of this study and the recognised advantages that prepare students for real-life environments, 3D-printed teeth should be integrated into dental education throughout. 3D-printing technology allows educators to reproduce any tooth shape and/or variation of the root-canal system found in endodontic classifications. Further technical development of 3D-printed teeth will provide the basis of education in integrated medical-dental teams and improve patient-centred care in future.[38]

5 | CONCLUSION

The questionnaire allowed the measurement of dentistry students' perceptions and experience of endodontic training with different models. The new 3D-printed tooth was suited to training undergraduate students in endodontic procedures. However, trainees still preferred extracted human teeth to the 3D-printed teeth with respect to their physical features. Nevertheless, students easily identified the training advantages of the 3D-printed tooth, such as its cleanliness, availability and uniformity, as well as the standardisation of training opportunities and assessment with complex root-canal configurations it provides.

The new 3D-printed tooth, thus, expands learner opportunities in addition or prior to training with extracted teeth. It is a highly feasible option for hands-on preclinical training purposes before students move onto their training with real patients.

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CONFLICT OF INTEREST

All authors declare that there is no conflict of interests.

AUTHOR CONTRIBUTIONS

All the authors were involved in the form and/or study design and contributed critically to the final preparation of this article, including approving the final version of the manuscript. Stefan Keß designed the 3D-printed tooth. Sarah König and Gabriel Krastl designed the study. Sarah König and Markus Kolling wrote the final study protocol and drafted the manuscript. Markus Kolling, Norbert Hofmann and Sebastian Soliman ran the study. Markus Kolling collected the results and analysed the data. Joy Backhaus assisted in statistical analyses.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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