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Automated outcome scoring in a virtual reality simulator for endodontic surgery

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ABSTRACT

Background and objective: We address the problem of automated outcome assessment in a virtual reality (VR) simulator for endodontic surgery. Outcome assessment is an essential component of any system that provides formative feedback, which requires assessing the outcome, relating it to the procedure, and communicating in a language natural to dental students. This study takes a first step toward automated generation of such comprehensive feedback.

Methods: Virtual reference templates are computed based on tooth anatomy and the outcome is assessed with a 3D score cube volume which consists of voxel-level non-linear weighted scores based on the templates. The detailed scores are transformed into standard scoring language used by dental schools. The system was evaluated on fifteen outcome samples that contained optimal results and those with errors including perforation of the walls, floor, and both, as well as various combinations of major and minor over and under drilling errors. Five endodontists who had professional training and varying levels of experiences in root canal treatment participated as raters in the experiment.

Results: Results from evaluation of our system with expert endodontists show a high degree of agreement with expert scores (information based measure of disagreement 0.04-0.21). At the same time they show some disagreement among human expert scores, reflecting the subjective nature of human outcome scoring. The discriminatory power of the AOS scores analyzed with three grade tiers (A, B, C) using the area under the receiver operating characteristic curve (AUC). The AUC values are generally highest for the {AB: C} cutoff which is cutoff at the boundary between clinically acceptable (B) and clinically unacceptable (C) grades.

Conclusions: The objective consistency of computed scores and high degree of agreement with experts make the proposed system a promising addition to existing VR simulators. The translation of detailed level scores into terminology commonly used in dental surgery supports natural communication with students and instructors. With the reference virtual templates created automatically, the approach is robust and is applicable in scoring the outcome of any dental surgery procedure involving the act of drilling.

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1. Introduction

A variety of computer-based simulation systems have been developed as a way to address the limitations of traditional skill training approaches and dental schools have begun to incorporate simulators into their curricula. Among the various types of simulators, Virtual Reality (VR) simulators are becoming popular as they have the ability to record kinematic data on how a user performs each step of a task, with numerous dental VR systems developed academically and commercially [1–12]. Addition of mechanisms to provide formative feedback would greatly increase the value of such systems.

Effective formative feedback requires assessment of outcome, of procedure, and of the relation of procedure to outcome, coupled with the ability to communicate the assessment in a language natural to dental students. In this study, we take a first step toward such a comprehensive approach to automated formative feedback by presenting the first algorithm for outcome scoring in the challenging area of endodontic surgery. All existing outcome assessment techniques in VR dental simulators apply only to cavity preparation and tooth extraction; they do not yet support outcome

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assessment for endodontic surgery. Our approach provides scores to the 3D voxel structure commonly used in VR dental simulators at a sufficient level of detail to allow correlation with procedure kinematic variables collected by such simulators. The fine-grained voxel level scores provide the precise error information that can be difficult to quantify in irregular 3D objects such as teeth with complex internal anatomy. To effectively communicate outcome score results, detailed level scores are translated into the language of the coarser level standard scoring system used by dental schools. The algorithm has been implemented for the procedure of access opening to the root canals. Agreement between system scores and those of expert endodontists is evaluated on fifteen outcome samples with a range of error types and severity. Results show a high degree of agreement between system scores and those of experts, while at the same time highlighting the variability in the subjective expert judgments. Automated outcome scoring can help to address such variability and lead to better standardization of assessment, which is an issue of ongoing concern in dental schools [44–46].

1.1. Related work

Surgical skill relies on both psychomotor and cognitive proficiency [13]. In conventional skill training approaches, feedback lacks granularity and proximity since only summative feedback is usually available and it is almost impossible to immediately evaluate every surgical training exercise [14]. Having the potential to provide both formative and summative assessment, intelligent tutoring systems (ITS) conveniently fill this gap and are integrated in medical education and surgery training curricula to provide assessment, feedback, and individualized instruction. Examples of such work related to techniques to ITS modeling in particular, include adaptive pedagogical modeling [15], and personalized adaptive learning [16]. The studies on the techniques to improve assessment performance [17–20], the quality of feedback by integrating of natural-language conversational/dialogue-based feedback [21] and providing hints (a form of feedback) [22] are also evidence in the literature. ITSs are also in the non-technical skills training and assessment such as problem solving [23], communication [24], team-behaviors [25], and cognitive skills for diagnosis [16]. Nowadays development of surgical skill assessment has received new breath with the use of educational data mining [26] and learning analytics [27]. In general, both statistical and cognitive modeling are inexorably linked in such approaches. The statistical modeling involves mathematical abstraction of student behavior measurements such as operation time, speed, hand movements, force, torque for surgical skill assessment whilst cognitive modeling involves with knowledge-to-task mapping such as investigating surgical skill learning and forgetting over time [28]. Although integration of ITS in surgical skill training is common in medicine in general, assessment and feedback in dental surgical skill training is still in its early stage.

Traditional assessment in dentistry has involved examination on prepared teeth using the glance and grade approach [29] with subjective judgment. Attempts to evaluate tooth preparation objectively include the use pulpal floor measuring instruments [30], CAD systems [31], and computer-based approaches using simulators discussed earlier. The need for valid objective assessment using simulators has been noted since early 2000 [32], yet the integration of effective grading and evaluation systems using simulators into curricula is still open to research.

Among existing dental skill training simulators, the Dentsim [4] and EPED [2] simulators provide training in intracoronal and extracoronal restoration by using plastic teeth and tracking kinematic data of the instruments using sensors. With limited internal anatomical and pathological variations in plastic teeth, the trainee's opportunity for exposure to a range of examples with anatomical variation during training, an important aspect of the skill training [33,34], is limited. While real time assessment is possible via tracking sensors, the tracking can be effected by the way the handpieces are handled.

The number of voxels cut in the operating area by a novice compared to skilled dentists is a commonly used metric for outcome assessment. Examples include the percentage of caries removed, the percentage of healthy tissue removed and injuries (e.g. pulp exposed) considered in cavity preparation [11,35] and how much the operator has carved into risk areas by measuring the removed amount of bone, enamel, dentin and pulp on the virtual tooth in tooth extraction [10]. Although a significantly different number of voxels removed in each area can indicate serious problems in the procedure, a similar number of voxels removed does not always indicate error-free performance.

Much work on developing metrics for feedback has been done in the context of otology surgical skill training simulators. Sewell [36] presented 16 metrics evaluating mastoidectomy performance, consisting of four major subcategories including bone removal, drilling and suctioning technique, proper exposure of critical anatomic structures, and forces and speed of the drill. Percentage values above/below threshold values based on prior data and the instructor-determined thresholds are provided to the trainee. Kerwin et al. [37] present an approach to automated scoring of virtual mastoidectomy performance on a voxel level. Firstly, they create a fully partitioned segmented dataset by defining surgically important regions on an iconic temporal bone. Then using earth mover's distance (EMD), parts of an expert-drilled bone are compared with a student-drilled bone. A decision tree is then created using the features derived from these comparisons to determine scores of resident surgical performance. By comparing with multiple expert examples, the score is averaged to provide a reliability metric. The VR epidural simulator by Vaughan et al. [38] also provides training assessment scores. The time taken, speed, angulation, the severity and other aspects of injuries resulting from errors are considered in computing the score.

2. Methods

2.1. Simulator

We employed the VR dental simulator developed by Rhienmora et al. [39]. The tooth model in the simulator is stored in the form of a three dimensional grid of voxels representing the density of the structure at each point using a value between 0 and 255 with 0 representing an empty voxel.

2.2. Procedure

We have selected access opening preparation of the root canal treatment to demonstrate and evaluate our approach. The procedure exclusively involves drilling, which is supported by the simulator, and the outcome is challenging to score, being a complex function of the internal tooth anatomy. In this stage, the endodontist drills a small hole through the surface of the tooth crown to gain access to the pulp chamber and root canals for treatment. The ideal result is an unobstructed passageway to the pulp space and the apical portion of the root canals. The ideal shape of the opening is a function of the tooth shape, tooth size, and the number and location of the root canals.

2.3. Score cube

According to Schmidt's schema theory of motor learning [40], the motor program is driven by the parameters of the proposed

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