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Survey on multisensory feedback virtual reality dental training systems

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Abstract

Compared with traditional dental training methods, virtual reality training systems integrated with multisensory feedback possess potentials advantages. However, there exist many technical challenges in developing a satisfactory simulator. In this manuscript, we systematically survey several current dental training systems to identify the gaps between the capabilities of these systems and the clinical training requirements. After briefly summarising the components, functions and unique features of each system, we discuss the technical challenges behind these systems including the software, hardware and user evaluation methods. Finally, the clinical requirements of an ideal dental training system are proposed. Future research/development areas are identified based on an analysis of the gaps between current systems and clinical training requirements.

Introduction

Pre-clinical dental training experiences are important for novice students to gain familiarity with the surgical operations, to acquire knowledge of anatomical structures within oral cavity and to master dexterous sensorimotor skills.

There are currently two major training methods utilised by students to acquire patient treatment skills: practice on typodonts (artificial teeth and jaws) mounted in phantom heads or on live patients. Typodonts have many limitations including physical properties (such as stiffness, friction) being vastly different from real teeth, high cost and environmental pollution in the manufacturing process. Extracted teeth, in comparison, may also be mounted into a phantom head, providing higher fidelity of physical properties than artificial teeth and, however, may be difficult to obtain. Compared to the use of a phantom head, a more effective way to train is to practice on live patients. However, this exposes patients to risks because of insufficient skills of novices. In addition, some patients are unwilling to be treated by training clinicians.

In recent years, computer-based dental simulation education has become an active area (1–3). A benefit of virtual environments containing various surgical instruments is that student can utilise an interface such as a mouse or a keyboard to control virtual surgical instruments to accomplish various surgical tasks. However, sensorimotor skills are difficult to be learned using these methods. In the past twenty years, haptic-based virtual reality (VR) became a booming and new branch of human–computer interaction. Therefore, haptic-enhanced VR simulation is proposed as an alternative methodology to provide the sensorimotor training needed as part of the dental curriculum. The future of VR dental simulation is promising because of both its technical advantages and social requirements (4, 5). Because of inadequate dental healthcare providers in many regions in the world, including Asia, Africa and Latin America(6), more dentists are needed to be trained, and VR dental simulation may be a supplement to traditional training methods to help meet these urgent training needs.

In the past decade, several VR dental training simulators with haptic–visual–audio feedback have been developed (1). Because of a lack of commonly accepted standards, these simulators have big differences not only in design and algorithms, but also in function and evaluation methods. This manuscript reviews existing dental training simulators, compares their differences and presents future research trends and development.

Current dental simulators

Historical development of dental simulators

In 1990's, Ranta et al. introduced the concept design of virtual reality dental training system (VRDTS) to practice cavity preparation (7). VRDTS (8) was further developed by Novint Technologies in collaboration with the Harvard School of Dental Medicine, allowing for virtual restoration of teeth. (Detailed specifications of the VRDTS are summarised in Table 1).

In 2001, the Iowa dental surgical simulator (IDSS) prototype was developed by the College of Dentistry at the University of Iowa and Graphical Representation of Knowledge (GROK) Lab. The simulator was designed to teach and evaluate subtle tactile and surgical skills relevant to clinical detection of carious lesions on the surfaces of teeth and within surgically cut dentin (9).

In the past ten years, more powerful dental simulators have been developed with the capabilities of providing immersive haptic feedback.

PerioSim (10–12) was developed by the University of Illinois at Chicago (UIC) through joint efforts of the Colleges of Dentistry and Engineering and designed especially for periodontics, which can simulate three typical operations including pocket probing, calculus detection and calculus removal. This system focused on probing different tissues around tooth.

Kings College London (KCL) dental school developed the prototype I of Haptic Technology Enhanced Learning (HapTEL) in 2008 and prototype II in 2010 in collaboration with the University of Reading. Their system allows users to learn and practice procedures such as tooth drilling, caries removal and cavity preparation for tooth restoration (13).

The Virtual Dental Patient (VDP) (14, 15) was developed by Aristotle University of Thessaloniki, Greece, to aid users in becoming acquainted with tooth anatomy, handling of instruments used for drilling as well as challenges associated with the drilling procedure.

The VirDenT system prototype was developed by Ovidius University to help users to learn how to prepare teeth (crowns and bridges) for ceramic crowns (16–19).

In Beihang University, China, Wang et al. (20–22). developed two generations of the *i*Dental system. The *i*Dental system can simulate typical periodontal procedures, including pocket probing, calculus detection and calculus removal. In addition, it can be used to practice drilling, removal of tooth decay and bimanual dexterity exercises such as use of a scaler to remove calculus whilst also holding a mirror in the other hand to retract the tongue.

Besides research prototypes developed in academic laboratories, there are also several commercially available dental simulators.

Forsslund Systems (23, 24) was developed by Forsslund Systems AB in 2008 to provide VR training for practicing dental drilling and wisdom tooth extraction. The core components of this system are the Kobra and FS-Wisdom, whilst the Kobra simulator is the set of hardware upon which the software application FS-Wisdom runs.

The Simodont Dental Trainer (25, 26) was developed by MOOG Inc., in collaboration with the Academic Centre for Dentistry Amsterdam (ACDA). It can simulate drilling, removal of tooth decay, restoring cavity preparations, crown and bridge preparations as well as mirror reflection. In addition to practicing manual dexterity skills, the system allows users to select virtual patient profiles and then perform diagnosis, treatment planning and provides automatic user evaluation.

The VOXEL-MAN Dental was developed by the University Medical Center Hamburg-Eppendorf. It provided training of cavity preparation and carious lesions with automatic skills assessment. This simulator can model burs of different shapes, controlled by a foot pedal (27–29).

VirTeaSy Dental was developed by DIDHAPTIC (Laval, Pays De La Loire, France) which is a dental surgery training simulator initially designed for teaching implantology (30–32).

Representative images of all of the mentioned simulators are shown in Fig. 1. Apart from these simulators, there are also many other dental simulators with few reported technical details (33–45).

Comparison of current dental simulators

Table 1 summarises the features of currently available systems with regard to the following five aspects: (I) developer and target operations, (II) functions, (III) hardware and controls, (IV) system performance and (V) VR environment.

From Table 1, it can be seen that only four commercial products are available where the differences in the five features can be clearly identified. Potential users such as school administrators and dental students can decide whether these systems will fulfil their training requirements.

Furthermore, most existing simulators are specific to only one discipline of dentistry, such as endodontics, and none of them meet the training requirements for all areas of dentistry. It can also be found that only a few simulators provided immediate feedback on errors or score performance of trainees. As studied by Sigrist et al., this immediate feedback may help

TABLE 1. Comparison amongst current dental simulators

Specification	VRDTS (1999, USA)	IDSS (2001, USA)	VDP (2006, Greece)	VOXEL-MAN Dental (2007, Germany)	Forsslund (2008, Sweden)	Simodont (2009, Netherland)	PerioSim (2009, USA)	HapTEL (2010, UK)	VirDenT system (2011, Romania)	*i*Dental (2011, China)	VirTeaSy Dental (2011, France)
Type	Prototype	Prototype	Prototype	Commercial product	Commercial product	Commercial product	Prototype	Prototype	Prototype	Prototype	Commercial product
I. Developer and operations											
Univ./Corp.	Novint Technologies Inc. & The Harvard School of Dental Medicine	University of Iowa	Aristotle University	University Medical Center Hamburg-Eppendorf	Forsslund Systems AB	MOOG & ACTA	UIC	KCL & University of Reading	Ovidius University	Beihang University	DIDHAPTIC
Target Departments	①Endodontics	①Endodontics	①Endodontics	①Endodontics	①Endodontics	①Endodontics; ②Prosthodontics.	①Periodontics	①Endodontics	①Prosthodontics	①Endodontics ②Periodontics	①Endodontics, ②Prosthodontics ③Implantology
Operation Type	①Drilling, caries removal and cavity preparation, filling cavities.	①Detection of carious lesions.	①Drilling	①Cavity preparation; ②Carious lesions removal	①Drilling, wisdom teeth extraction.	①Drilling, decay removal, cavities filling; ②Crown and bridge preparation.	①Pocket probing, calculus detection and removal, scaling and root planning.	①Drilling, caries removal and cavity preparation.	①Tooth preparation (crowns and bridges); ②Teeth grinding.	①Drilling, decay removal; ②Pocket probing, calculus detection and removal.	①Drilling, caries removal ②Implant ③others
II. Function											
Functions	①Repeat and playback procedures many times.	N	①Assist experienced dentists to plan drilling, identify landmarks and plan their approach.	①Train manual dexterity and problem-solving skills; ②Additional cross-sectional images of tooth.	①Operations can even be replayed on a desktop computer.	①Select virtual patient profiles; ②Manual dexterity exercises	①Train the user how to select and manipulate the dental instruments properly.	①Replay the procedure; ②Allow quick calibration by self-indexing encoders.	①The user can operate following by an intelligent tutor simultaneously.	①Manual dexterity exercises	①Surgery planning; ②Surgery performing.
Feedback Sensory Channels	Haptic–Visual–Auditory	Haptic–Visual	Haptic–Visual	Haptic–Visual–Auditory	Haptic–Visual	Haptic–Visual–Auditory	Haptic–Visual–Auditory	Haptic–Visual–Auditory	Haptic–Visual	Haptic–Visual-Auditory	Haptic–Visual
Case-based Diagnose	NR	NR	NR	Y	N	Y	N	NR	NR	N	Y
Immediate Feedback	NR	NR	NR	Y	Y(Report)	N	N	NR	NR	N	N
III. Hardware and Control											
Display Type	Non-3D	Monitor screen	3D	3D	3D	3D	3D/AR	3D	A video display/AR	3D	3D
Haptic Device	PHANTOM Desktop	Impulse Engine 2000	PHANTOM Desktop	PHANTOM Omni	PHANTOM Omni/PHANTOM Desktop	Moog Haptic Master	PHANTOM Desktop	NOVINT Falcon	NR	PHANTOM Omni/PHANTOM Desktop	Virtuoso™ 6D Desktop
Tracking System	N	N	N	N	N	N	Motion tracking device	Camera head tracking unit	N	N	NR

Table 1. Continued

Specification	System: VRDTS (1999, USA)	IDSS (2001, USA)	VDP (2006, Greece)	VOXEL-MAN Dental (2007, Germany)	Forsslund (2008, Sweden)	Simodont (2009, Netherland)	PerioSim (2009, USA)	HapTEL (2010, UK)	VirDenT system (2011, Romania)	*i*Dental (2011, China)	VirTeaSy Dental (2011, France)
Virtual Drilling Control	N	NA	N	Foot pedal	Foot pedal	Foot pedal	N	Foot pedal	Foot pedal	Buttons on PHANTOM's stylus	Foot pedal
Physical Tissue	None	None	None	None	Mannequin	①A drill handle; ②A dental mirror	None	Cheek (Rubber)	None	None	None
Finger Rest Point	N	N	N	NR	N	Wrist fixture	N	Finger rest adjustable ring	NR	Additional physical object	Y
Sensor	NR	NR	NR	NR	NR	A force sensor in the drill hand piece	Force sensors.	NR	NR	N	NR
IV. System Performance											
System Expandability	N	N	N	Y	Y	Y	N	N	N	N	NR
Automatic Evaluation	N	Y	N	N	Y	Y	Y	Y	Y	N	Y
Experts' Database	NR	NR	NR	Y	Y	NR	Y	NR	NR	N	Y
Haptic–visual collocation	N	N	N	NR	Y, precision unknown.	Y, precision unknown.	N	Y, precision unknown.	N	Y, precision is 1.8 mm.	NR
V. VR Environment											
Oral Tissues/Tool	①Dental instruments (low speed drill, an explorer, two carvers, a carrier and a packer); ②Amalgam material; ③a single molar (enamel, dentin, caries and pulp).	①A plastic model of a patient; ②Teeth (enamel, healthy dentin and carious dentin).	①Head/neck ②Gums; ③Palate; ④Teeth; ⑤Tongue; ⑥Lips; ⑦Cheek; ⑧Larynx; ⑨Uvula.	①Teeth(enamel, dentin, pulp, and carious tissue); ②Burs with different shapes; ③Dental mirror.	①Bone ②Teeth (enamel, dentin, pulp and nerves).	①Mouth; ②Teeth (enamel, dentine, pulp, carious tissue); ③Dental mirror.	①Upper and lower dental arches (v. I); ②4-tooth mouth segment (v. II); ③bone (v. II); ④Gingiva; ⑤Teeth (32 in v. I; 4 in v. II); ⑥Calculus.	①Jaw; ②Teeth (enamel, dentine, pulp and cavity).	①Drill; ②Four teeth: upper right central incisor (11), left first upper premolar (24), left lower canine (33) and first lower molar right (46) ③Patient.	①Cheek; ②Tongue; ③Gingiva; ④Teeth(enamel calculus and carious tissue); ⑤Dental mirror.	①Cheek; ②Tongue; ③Gingiva; ④Teeth (enamel, dentin, caries); ⑤others
Haptic Interaction Type	Single-hand FF	Single-hand FF	Single-hand FF	Bimanual operation, single-hand FF	Single manual operation; Single-hand FF	Bimanual operation, single-hand FF	Single manual operation; Single-hand FF	Single manual operation; Single-hand FF	NR	Bimanual operation, two-hand FF	NR
Model	NR	NR	Surface model and Volumetric model	NR	Volumetric model	Surface model and volumetric model	Spring-damper model	Volumetric tetrahedron model	NR	Surface model and volumetric model	NR
Models Contact Type	Single-point contact	Single-point contact	NR	NR	Single-point contact	Single-point contact	Single-point contact	Single-point contact	NR	Multipoint contact	NR

① Y, yes; N, no; NA, not applicable; NR, not reported; v., version; ② FF, Force Feedback; GHOST, General Haptic Open Software Toolkit.

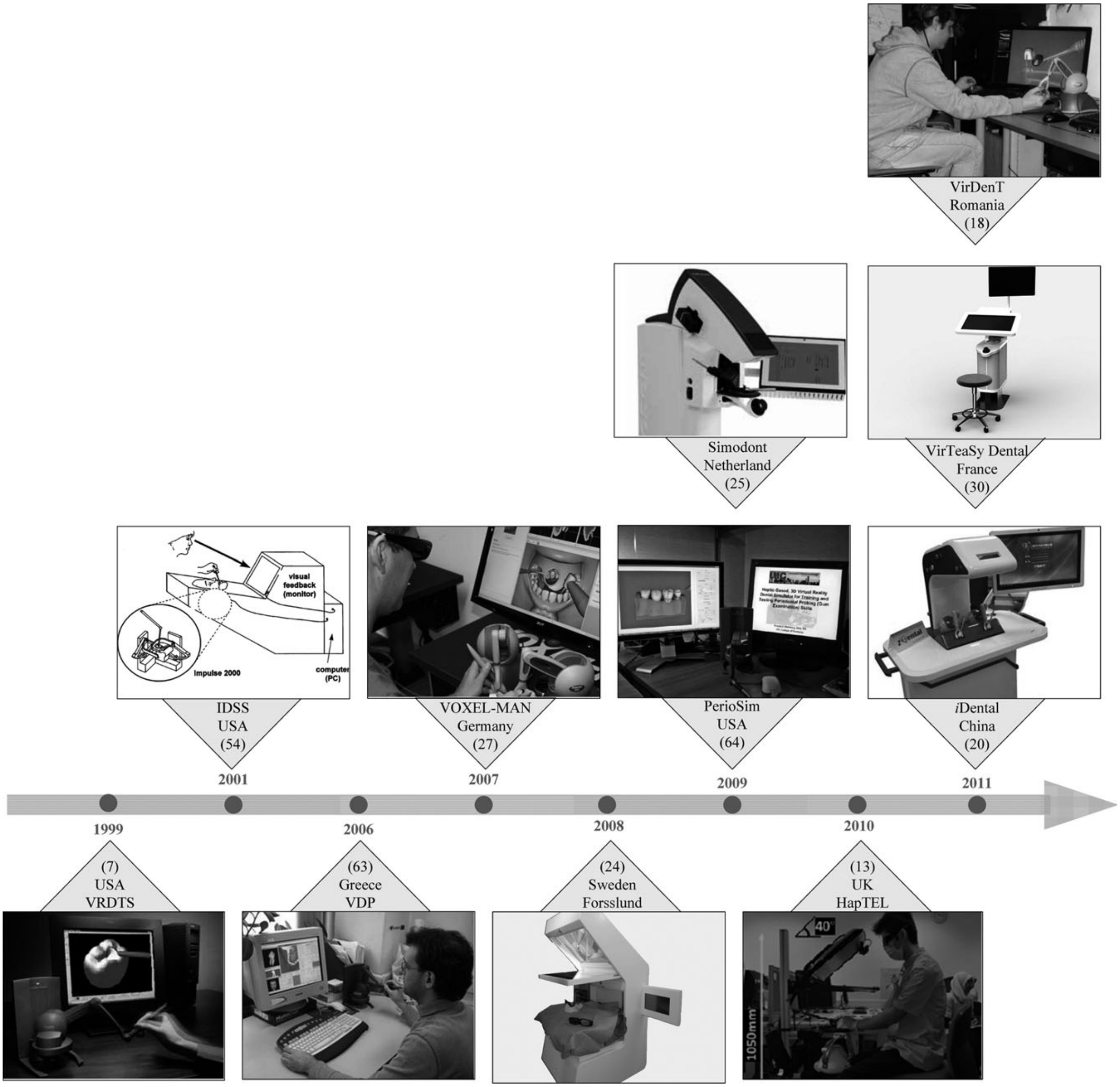


Fig. 1. Current dental simulators.

trainees to identify their weaknesses and correct wrong manipulation behaviours (46).

Analysis of current simulators: technical perspectives

Software

Software is the key element of a dental simulator. The functions of software are twofold: (i) creating a virtual environment including virtual teeth, virtual dental tools and virtual tissues in oral environment, and (ii) providing high-fidelity haptic–visual–audio rendering or synthesis algorithms to simulate the real time interaction between various virtual instruments and oral tissues. To fulfil these functions, the following components constitute key challenges for development of high-performance software: haptic modelling method, haptic rendering algorithm, collocation of haptic–visual feedback and courseware.

Haptic modelling method is the foundation for constructing a VR environment. Volumetric (voxel-based) models have been widely adopted to render the teeth and implemented drilling process by the majority of simulators including Simodont, *i*Dental, HapTEL, Forsslund and VDP (Table 1). A sphere-tree model is also used to model teeth and tongue, and thus facilitates multiregion contacts and deformation simulation (21).

Haptic rendering algorithm is the key technology in software to simulate the collision/contact between the dental tools and the oral tissue, compute contact force/torque and impose them on a user's hand through the haptic devices. Most simulators can only simulate contact force between rigid bodies, whilst only a few can simulate deformation under 1 kHz update rate. In addition, the majority of simulators can only simulate single-hand force feedback, whilst bimanual force feedback is required for higher efficiency of the haptic rendering algorithm. In addition, most of the simulators are single-point contact during haptic interaction except a few systems that have extended point-based rendering to six degree of freedom (six-DoF) haptic rendering of multiregion contacts (21).

Collocation accuracy of haptic–visual feedback determines the fidelity of the human perception in the VR environment, which refers to the degree of overlap between the virtual tool in VR environment and the hand-held handle in the real world. The higher the haptic–visual collocation accuracy, the better the illusion of immersion that can be obtained. As shown in Table 1, only Simodont, *i*Dental, HapTEL and Forsslund provide haptic–visual collocation function using either a half-reflective mirror or a miniaturised optical projection system. Three of them did not provide accuracy data whilst only one system reported the accuracy of 1.8 mm using a calibration method (47).

Courseware is critical for students to acquire sensorimotor skills by providing sufficient training experiences through elaborately designed exercises. Well-designed courseware should provide comprehensive functions, progressive training protocols, training on usage of dental instruments, manual dexterity exercises, hand-eye coordination experience, record and playback of training process, etc. However, as shown in Table 1, none of the existing simulators can completely provide these functions.

Hardware

Two types of hardware are necessary for a multisensory dental simulator: 1) an ergonomic multisensory collocation platform to provide immersive and user-friendly interaction between the human operator and the virtual environment and 2) high-performance haptic devices (or force feedback devices) to provide stable and high-fidelity force/torque feedback to the human operator's hand.

The hardware of existing dental training simulators varies a lot, both the appearance of the multisensory collocation platform and the force feedback devices. Figure 1 illustrates the appearance of these simulators. The adopted haptic devices of some simulators are summarised in Table 2. A large stiffness of a haptic device is crucial to simulate contact against hard tissues like enamel. For most simulators, impedance displayed haptic devices such as Phantom Omnis are used. This type of devices cannot simulate sufficient stiffness, and the maximum stiffness is about 3 N/mm, which is much less than the contact stiffness of hard tissues like enamel (48). In the Simodont system, the admittance control strategy is adopted and the related device, Haptic Master, can simulate stiffness up to 50 N/mm (49). To utilise this control strategy, high-performance force sensors are needed to detect subtle changes of human interaction forces.

Furthermore, the degree of freedom of force feedback (DoFFF) of all surveyed dental simulators except VirTeaSy Dental equals or less than three, which is not enough to simulate six-DoF haptic interaction between dental tools and oral tissues. As frequent translations and rotations normally occur during the manipulation of the tool within the narrow oral cavity, multiregion contacts between the surgical tool and oral tissues may lead to six dimensional force and torque, which makes the simulation of six-DoF haptic feedback become an indispensable requirement (20).

Performance evaluation

Performance evaluation is indispensable for a surgical simulator to become an acceptable educational tool. Performance evaluation includes methods and protocols designed to evaluate the usefulness of a simulator, and courseware to implement the surgical training protocols and to evaluate the manipulation performance based on recorded data of trainees.

Typically, subjective/qualitative and objective/quantitative methods are used for simulator evaluation. Qualitative methods aim to discover system deficiencies and design flaws that require modification, whilst quantitative methods mainly aim to evaluate functional efficiency. These evaluations provide important lessons for identifying limitations of existing simulators and guiding future research and development directions.

Amongst the currently available dental simulators, with the exception of VDP and VRDTS, all have implemented evaluations as part of their system. Simodont (50, 51), *i*Dental (prototype I) (20), VOXEL-MAN Dental (28, 29) and VirTeaSy Dental (31) have all been evaluated both subjectively and objectively; VirDenT (14) has only implemented objective evaluation whilst HapTEL (13, 52), Forsslund (prototype I) (23), PerioSim (prototype I) (11, 53) and IDSS(54, 55) have only implemented subjective evaluation. Table 3 summarises the evaluation methods and main results of current dental simulators. Although most systems have received positive feedback from trainees, whether or not there has been skill transfer from simulation to real dental operations needs to be validated by more rigorous studies. There are no commonly accepted standards on evaluation methods and criteria.

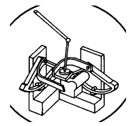
Identified research and development topics

In spite of the great achievements made by existing simulators, many technical and application challenges still remain in designing a useful dental simulator. Virtual reality dental simulators are still in their early stages of development, and a large gap exists between current VR simulators and clinical practice. Many key technological advances including modelling, algorithms and functionalities are still in need of improvement.

Gaps between existing systems and clinical requirements

Compared to clinical training on live patients, the following summarises the gaps that exist between dental simulators and clinical experiences:

TABLE 2. Major parameters of haptic devices used in dental training simulators

Haptic device	Simulator	DOF	DOFFF	Workspace	Size	Stiffness	Picture of device
PHANTOM Desktop (Geomagic Touch X)[1]	VRDTS; VDP; Forsslund; PerioSim	6	3	>160 W × 120H × 120D mm	143W × 184D mm	*x*-axis > 1.86 N/mm; *y*-axis > 2.35 N/mm; *z*-axis > 1.48 N/mm	
PHANTOM Omni (Geomagic Touch)[1]	Forsslund; VOXEL-MAN Dental; *i*Dental	6	3	>160 W × 120H × 70D mm	168W × 203D mm	*x*-axis > 1.26 N/mm; *y*-axis > 2.31 N/mm; *z*-axis > 1.02 N/mm	
NOVINT Falcon[2]	HapTEL	3	3	101 W × 101H × 101D mm	228W × 228H × 228D mm	8 N/mm	
Force feedback robot arm (adapted from Moog Haptic Master) (25)	Simodont	6	3	100 W × 100H × 100D mm	NR	~50 N/mm	
Impulse Engine 2000 (54)	IDSS	3	2	NR	NR	NR	
Virtuoso™ 6D Desktop[3]	VirTeaSy Dental	6	6	521 × 370 × 400 mm 270° × 120° × 250°	NR	Translation (max): 1 N/mm Rotation (max): 4Nm/rad	

NR, not reported; DOFFF, degree of freedom force feedback.
[1]Geomagic, Inc., USA. (www.geomagic.com).
[2]Novint Technologies Inc., USA. (http://www.novint.com).
[3]HAPTION S.A., France. (www.haption.com).

- As shown in Table 1, most existing dental simulator only provides training scenarios for one type of dental procedure. Only Simodont, *i*Dental and VirTeaSy Dental cover more than one dentistry department. For more comprehensive use in dental education, future simulators should support a multitude of types of clinical procedures (32), including endodontic, periodontic, prosthodontic, surgical and paediatric dental procedures.
- Existing dental simulators only provide training of a single tooth or an arch, which is not sufficient to train all the fine motor skills of accurate motion and force control within the oral cavity including interactions between dental instruments and delicate oral tissues (20). Realistic modelling and haptic simulation of a complete set of oral tissues, including cheek, floor of the mouth, maxilla and mandible, lips, tongue, gingiva, 32 teeth (including enamel, dentin and pulp) are indispensable to provide fine motor skill learning in the narrow oral cavity environment.
- Potential advantages of virtual reality systems over traditional Phantom head should be further explored, including its use for simulation of common and/or rare pathological changes (56). Furthermore, a simulator could also simulate emergency scenarios that could offer students opportunities for learning how to manage patients in a high stress workload situation (57).
- Fidelity of haptic–visual–audio feedback and their spatial and temporal synchronisation need to be improved. Compact haptic devices with sufficiently large stiffness and sufficient dexterity are still a big challenge (13). It is still an ongoing topic to develop high efficiency haptic rendering algorithms that can provide six dimensional force and torque feedback and can simulate multiregion contacts between dental tools and deformable oral tissues, whilst maintaining high precision of haptic–visual collocation.
- Enhancement of the functionality of training courseware is needed to meet international training standard for dentists, including training of correct dental instrument selection, exercises of bimanual coordination dexterity, and recording and playback of training exercises (2).

Future research topics

Major future research topics can be divided into the following aspects: fidelity of multisensory feedback, ergonomics of training platform and effectiveness of evaluation methods.

TABLE 3. Summary of evaluation methods adopted by current dental simulators

	Clauses					
Simulator	Mode	Parti. Num.	Aim	Methods	Results	Conclusions
IDSS (2001)	Objective	NR	NR	NR	NR	NR
	Subjective	12	To identify and correct design flaws in the prototype simulator.	①Pilot tests and a group interview; ②Participants were randomly divided into two groups—Group A and Group B; ③Group A 'explored' one tooth for caries using the joystick and then switched to the explorer to probe the second tooth; ④Group B explored a tooth first using the explorer and then probed the second tooth using the joystick; ⑤Participants within each group alternated which tooth they probed first; ⑥The research design was a 2 × 2 factorial design (crossover).	The practitioners were generally satisfied with the simulator, but specific areas need to be addressed.	①The effect of grip design and the quality of the force feedback device were quite important, rather than graphics; ②The vibration of the device on the tooth surface dominated the participant's experience; therefore, further work is required to reduce the distracting vibrations.
VOXEL-MAN Dental (2007)	Objective	41	To evaluated the transfer of skills from virtual simulator to the cadaveric model.	①Participants were divided into two groups – Group 1 and Group 2; ②Training Group 1 apicectomy on the VOXEL-MAN system; ③Both of Group 1 and Group 2 conduct an apicectomy on a cadaveric porcine jaw.	The performance of Group 1 was significantly better than Group 2.	①The Voxel-Man simulator improved the practical abilities of young residents; ②The simulator had great potential on improving the traditional methods of teaching oral surgery.
	Subjective	53	To evaluate the Voxel-Man simulator and obtain user perceptions,	①Participants performed virtual apicectomy and then filled out a questionnaire.	①About 92.7% of participants recommended the simulator as an additional tool in dental education; ②About 81.1% thought the force feedback as good or very good; ③About 86.8% valuated the 3D spatial perception as good or very good.	Participants were generally satisfied with the simulator.
Forsslund (2008) (Prototype I)	Objective	NR	NR	NR	NR	NR
	Subjective	4	To verify design decisions and get input for modifications in future iterations	①Cooperative Evaluation, that is 'think aloud' method; ②A preliminary free exploration of the simulator's capabilities; ③followed by performing the mandibular bone carving part of the extraction procedure.	①The position and angle of the patients head should be laying down and accessed from the side; ②It is necessary to have a hand support and a contextual (polygon mesh) head; ③The surgeons expected the carving to support a sweeping motion; ④There were requests to interactively control the surgical tissue flap with a wound hook.	①More research is needed relating to what the sweeping motion is and how to support it; ②Overall feedback was positive in the sense that the surgeons clearly saw the potential and that simulator based surgical training in this field was within reach.

Table 3. Continued

Simulator	Clauses: Mode	Parti. Num.	Aim	Methods	Results	Conclusions
Simodont (2009)	Objective	28	To investigate if skills developed in VR were transferred to reality.	①Ten trained in the traditional phantom lab, 10 trained in the Simodont laboratory and 8 acted as a control group; ②Performing a manual dexterity test at the phantom head laboratory and Simodont.	All students performed better after little or more training, independent of the training environment.	①Skills were transferred successfully; ②The Simodont appeared to be a useful instrument.
	Subjective	45	To evaluate the perception of the level of realism of the Simodont simulator.	①All participants carried out a drilling exercise on the Simodont; ②and then filled out a questionnaire	①The feedback of the system was clear but limited, ②None think that the Simodont can completely replace the teacher; ③About 85% of the students and 70% of the teachers were quite positive about the realism of the various aspects of the Simodont.	①The system potentially can be successfully implemented in the dental curriculum; ②The difference in perception of realism between the teachers and students is probably due to their reference environments
PerioSim (2009) (Prototype I)	Objective	NR	NR	NR	NR	NR
	Subjective	30	To judge the reality and usefulness of version I in training and evaluating basic procedural skills of students.	①A PowerPoint presentation on one screen provided instructions for the simulator use while another monitor contained the simulator program; ②The subjects were individually guided through a series of onscreen tasks that taught participants to use and adjust to the simulator. ③A questionnaire about the dental procedures.	①The images are very realistic for teeth and instruments, but less so for gingiva; ②The probing instruments were realistic and the instruments marking easy to read; ③Faculty believed the simulator had a high training potential, and anticipated incorporating this device into teaching.	The self-contained teaching and training program in periodontal probing should aid students in the development of necessary dental tactile skills.
HapTEL (2010)	Objective	NR	NR	NR	NR	NR
	Subjective	144	To evaluate the hardware and software of the hapTEL impact on teaching and learning.	①Observation, video, questionnaires and data capture were used to record students' experiences; ②Evaluations focus on operational body position, hand position and interaction with pod, haptic device and dental tool, effect of head tracking and stereo vision towards training.	①The haptic device linkages were considered too high; ②The inertia and the internal friction were not solved to the dental tutor's satisfaction; ③The haptic device did not suffice in quality and could only provide one point of force feedback to the dental tool head.	Finger rest, dental tools, software, and collocation among hand, eye and tool should be merited high priority.
VirDenT (2011)	Objective	5 in phase I; 10 in II; 40 in III.	①Testing the qualities of the VirDenT system to correct any deficiencies; ②Evaluating the use of the system by third-year students.	①Practicing the preparation of the tooth 11; ②One week of testing; ③Each participant has 2 hours of training; ④The basic unit of performance is the number of hours required for the skills acquisition using the VirDenT system.	①Teachers needed double time to acquire the ability to work with the system compared with 3 students of the group who had the best results; ②Big differences between the skills demonstrated by students (Phase II);	①Although the application of the system is in its infancy, the system presents an important potential; ②High possibility of error by lack of support for the operator's arm; ③It is necessary to create a warning system for the mistakes committed by the student.
	Subjective	NR	NR	NR	NR	NR

Table 3. Continued

Simulator	Clauses: Mode	Parti. Num.	Aim	Methods	Results	Conclusions
*i*Dental (2011) (Prototype I)	Objective	29	To evaluate the effect of the dental simulator by analysing difference between the two groups.	①Divide the subjects into two groups: dental experts and graduate students; ②Same operation was used as test target, their operation data were recorded in real time; ③Perform three periodontal procedures including periodontal pocket probing, calculus detection, and removal.	①Penetration between tool and teeth or cheek will greatly decrease the fidelity of the simulation, ②Key research topics that will enable haptic technology to be effective in a practical simulator were identified, including simulation of deformable body and occlusion of tongue and cheek on teeth, etc.	①It is necessary to utilise 6-DOF haptic device with both force and torque feedback in dental simulator; ②It is needed to extend point-based rendering to 6-DOF haptic rendering of multiregion contacts.
	Subjective	29	To find the interest of subjects and identify limitation of the simulator.	①Score sheets based on several evaluation architecture were designed; ②For every component, there are four levels for the score.	①Users give high scores on the graphic rendering effect of the simulator, as well as the shape and colour of most tissues except shape of calculus; ②The continuously increasing force effect was not realistic enough; ③The fidelity of calculus removal is realistic, but the magnitude of the removal force should be versatile.	①Fidelity and degrees of convenience for usage need to be improved; ②The VR dental simulator will provide more flexible training curriculums and more objective evaluation than traditional training ways; ③It is necessary to provide simulation of the lateral force from gingiva to probe.
VirTeaSy Dental (2011)	Objective	26	To evaluate the performance of dental students versus prosthodontics residents on a simulated caries removal exercise.	①Two groups: novice and experienced; ②Be presented with a brief verbal overview of the experiment; ③video demonstrated how to use the simulator; ④completed two tutorial exercises to familiarise with the simulator; ⑤drill a hole in three block with different density; ⑥remove of a low-density cross from a high-density block, ⑦complete a caries removal exercise	Performance of experienced group was significantly better than novice group	The simulator could distinguish performance between users with different levels
	Subjective	26	To provide an initial assessment of the simulator's construct validity	Fill out a questionnaire	Novice group was more positive and enthusiastic to the simulator	Results supported the construct validity of this simulator
1999 VRDTS	Objective	NR	NR	NR	NR	NR
	Subjective	NR	NR	NR	NR	NR
2006 VDP	Objective	NR	NR	NR	NR	NR
	Subjective	NR	NR	NR	NR	NR

VRS, virtual reality computer-assisted simulation system; CS, contemporary non-computer-assisted simulation system; NR, not reported.

Fidelity of multisensory feedback

The fundamental question for fidelity needs to be studied, that is what are the necessary functions and performance specifications needed for a dental simulator to be useful? Specifically, how much fidelity of haptic feedback is required to maintain successful training of dexterous sensorimotor skills? Fidelity of haptic simulation is crucial for students to learn the correct force patterns and to acquire dexterous sensory-motor skills. Two important aspects including haptic device and haptic rendering determine the fidelity of haptic simulation. Six-DoF haptic devices with both force and torque feedback and sufficient dexterous orientation work space are needed. Devices with high maximum stiffness should be developed to simulate hard contact against enamel. The shape and size of the device handle should be customised to be similar to that of dental tools. Many research efforts have been made to improve haptic rendering on six-DoF for fine manipulation (21, 58). However, more research is necessary, for example, to simulate subtle force feeling when the dental tool interacts with pathological changes such as calculus and decay.

Fidelity of graphic simulation is another important area of research. Users' stereoscopic impression in the VR environment is different from that of the real world. The resolution of the image and the fidelity of stereoscopic graphic rendering are crucial for training hand-eye coordination skills. Therefore, eliminating penetration between tool and teeth or cheek, enhancing stereoscopic acuity and depth perception may bring significant benefits for improving visual simulation fidelity.

It is still an open research question that how much realism is needed to provide effective fine motor skills/clinical training. To explore this question, one possible way is to perform longitudinal and randomised control studies on observing the motor learning and skill transfer effect using dental simulators with varied levels of realism (59–62).

Ergonomics of the training platform

As revealed in previous training studies, a reliable finger rest is an indispensable part of clinical practice (20). It is necessary to maintain correct hand posture and exert accurate force in a correct direction. A frequently problem for trainee clinicians is lacking of a finger rest or difficult to find a reliable and ideal supporting point during clinical operations (13, 23). Although some simulators (e.g. Simodont, HapTEL and VirTeaSy Dental) have been designed to include supporting structures for fingers or wrist rests to avoid hands from just hanging in the air, the manipulation ergonomics are far different from those of clinical practice. For example, in clinical operations, the dental tool is grasped by the thumb, index and middle fingers, whilst the ring finger is pressed to the neighbour of the target tooth. This configuration of the four fingers provides a firm support for fine manipulations such as removing calculus using large forces. Therefore, more reliable, anatomically appropriate and stable finger rests need to be designed.

Hand grip position and force control are two key components of successful completion of a dental surgical procedure in an ideal and smooth manner. Curriculum needs to be developed for training users to learn correct hand grip position and force patterns for a given operational task.

Effectiveness of evaluation methods

A challenging problem for dental simulators is how they should be evaluated to provide convincing proof of their usability and clinical feasibility. As shown in Table 3, various evaluation methods have been adopted by developers to assess their dental simulator's performance. However, there is not yet a commonly accepted standard for evaluation of VR dental simulators. More studies are needed to compare the strength and weakness of various evaluation methods, including what control group methods are used (such as how to compare training outcomes between traditional and VR simulator trained groups) (50, 53). Furthermore, it is necessary to design a systematic evaluation framework that could combine the strength of subjective and objective evaluation methods. One possible way forward may be to examine current evaluation methods used for minimally invasive surgical simulators, or even flight simulators, and learn from their methodology.

Future development topics

Current VR dental simulators mainly focus on training basic or simple dental skills such as calculus detection and removal, pocket probing, tooth extracting and dental drilling. However, these simple and limited skills are far away from meeting all training requirements. Thus, more diversified functions need to be developed, such as simulation of emergency cases, communication between the trainee and the virtual patient, and system expandability.

Simulation of emergency cases

Emergency case simulation is very useful in flight simulation, for example, to teach the pilot how to manage emergencies such as an aircraft engine failure. This concept could also be utilised in the dental training systems, to simulate unexpected patient complications such as bleeding, trembling, drooling, sudden movements of mouth such that trainee learns how to adjust the motion or state of the dental instrument. For example, a sudden movement of the mouth should trigger an immediately shut down of the drill to avoid damage to patients' tongue or gingiva.

Communication between the trainee and the virtual patient

In real clinical operations, communication between a dentist and his/her patient is indispensable. Good communication can help ensure success of dental procedures and relief of patient' discomfort. During a procedure, patient may be nervous and apprehensive; hence, in order to ensure the dentist is able to complete the operation successfully, s/he should comfort the patient through appropriate communication. In the future, this kind of functionality could be added to VR dental simulators.

System expandability

System expandability can provide a chance for users to improve and customise their own simulators. A good simulator should allows users to add new functions into the system, such as new procedures covering more areas of dentistry, new patient scenarios, different teeth models and so on.

Conclusions

Compared to the wide acceptance of flight simulators in pilot training and certification, haptic-based VR dental simulation is just in its infancy. Despite its existing limitations, VR dental simulators present a novel tool in dental education. In contrast to existing training methods including the use of Phantom head models, VR dental simulators may bring unique capabilities such as simulation of emergency cases, quantitative recording and playback of operational processes. With improvements in simulation fidelity including haptic, visual and audio feedback, VR dental simulators are promising to become widely accepted tools for clinical training, surgical planning, rehearsal and certification.

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