Interactive Multi-Physics Simulation for Endodontic Treatment

Sebastian von Mammen, Marco Weber, Hans-Heinrich Opel
University of Augsburg, Augsburg, Germany
s.vonmammen@t-online.de,
marco-we@hotmail.com, drhho@gmx.de

Timothy Davison
University of Calgary
2500 University Dr. NW
T2N1N4 Calgary, AB, Canada
tbdaviso@ucalgary.ca

ABSTRACT
In this paper we present a novel approach to simulating dental treatment of root canals. Preceding interactive simulation approaches to dental training focus on preparing access cavities and working on the hard dentin of a tooth. Their common goal is to provide haptic feedback necessary to impart manual dexterity to students. In contrast, we focus on learning about the intricate complexity involved in root canal treatment, considering different root canal morphologies, differences in the texture of the pulp tissue as well as the interaction possibilities offered by different dental instruments at individual steps of the procedure. Due to this shift in focus, new computing challenges appropriate for physical interactions emerge. In this paper we elaborate on recent developments in realtime physics simulation and we demonstrate the backend mechanisms needed to drive more complex dental training simulations, amalgamating different representations for real-time physics calculations.

Author Keywords
Interactive Simulation; Virtual Reality; Training; Education; Dental Treatment; Endodontics;

ACM Classification Keywords
I.6.1 SIMULATION AND MODELING (e.g. Model Development). : Miscellaneous

INTRODUCTION
Treating the root canal of a tooth becomes necessary if its pulp tissue gets infected. The root canals are cleaned from the pulp, restored with a filling, and the access cavity is closed again. There are more than seven million root canal treatments each year in Germany alone [1]. Yet, it has been ascertained internationally that the rate of success of such endodontic procedures is not satisfactory. In part this might be due to inconsistent protocols [2, 3], partially to accidents during treatment, but mainly it is due to the persistence of infections in the root canal system [4]. The frequent failure to clean root canals does not come as a surprise considering the complexity of root canal morphologies (varying diameters, bifurcations, isthmuses, and dividing and merging canals) [5], the available assortment of instruments, and operation aids (mainly regarding magnification and illumination) [6]. Accordingly, the following quote from [7] stresses the need for system comprehension to achieve successful treatments: “A thorough understanding of the complexity of the root canal system is essential for understanding the principles and problems of shaping and cleaning, for determining the apical limits and dimensions of canal preparations, and for performing successful microsurgical procedures.”

Although there have been approaches to virtual simulation and training of root canal treatment, or *endodontic therapy* [8], they were rather limited in their scope, focusing on the first step of the procedure, e.g. [9, 10]. As a first step, the dentist needs to prepare an access cavity to reach the root canals' pulp tissue. This first step is soon learned by dentistry students training on extracted teeth or phantom teeth and it typically does not pose a great challenge. Next, the dentist would clean out the root canals, removing the pulp tissue as meticulously as possible in order to avoid the aforementioned persistence of infections. Loosening the soft pulp material is performed using a dental handpiece equipped with an according bur and by means of endodontic files. In order to thoroughly clean the root canals, they also need to be irrigated.

In this paper, we present an approach tackling these challenging tasks of endodontic therapy in virtual reality simulation from a real-time multi-physics perspective. The concept comprises the model representation, the computation of the interaction dynamics, and especially the coupling between different conceptual physical representations, i.e. rigid and deformable bodies. The remainder of this paper is structured as follows. In the next section, we briefly touch upon related work including virtual reality approaches developed for dental training and real-time physics approaches. Next, we explain our concept, detailing the process of asset generation, their physical representation and their physical interaction mechanics. Before summarising our contributions and providing an outlook on future work, we discuss our approach in the light of recent advancements in real-time physics simulation.

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RELATED WORK

Work related to our contribution can mainly be aligned with two directions: Virtual simulations for dental training and approaches to real-time physics computation. In this section, we briefly touch upon both these fields, starting with preceding virtual dental training approaches that only rely on rigid body dynamics.

Virtual Dental Training

In the 1990s, DentSim was introduced into the market [11]. It is nowadays used to train students at six universities across the U.S.A. It tracks the students' activities by means of video sensors that pick up signals from LED emitters that are integrated in the students' dental instruments. Based on this data, feedback can be provided about the students' treatment success, while working on phantom teeth. DentSim was the first system of its kind to undergo extensive validation, e.g. [12].

As mentioned in the introduction, a moderate number of computer-based dental training systems was developed that focused on haptic feedback. Among others, a multi-modal setup was presented that established a stereoscopic view by a shutter glass-filtered projection on a mirror just above an operation space [13]. Guiding an instrument for operating on a so-called phantom head was simulated relying on what is nowadays called a Sensable Phantom Omni device, a force-feedback contraption that offers three degrees of freedom at rather small dimensions. PerioSim[14], Voxel-Man [15], or the Virtual Reality Dental Training System [16] all utilise the Omni device to let the student acquire manual dexterity. In the context of endodontics, all these approaches only offer the preparation of the access cavity. Nowadays, there are numerous force feedback devices available and, accordingly, additional haptics-oriented concepts have been presented [17, 18]. Yet, to the knowledge of the authors there is not a single virtual reality solution that attempts to teach the complexity of endodontic therapy's actual challenge, namely cleaning root canals of complex morphologies.

Real-time Physics Approaches

Interactive simulations offer the means to manipulate model components to various degrees. Depending on the level of abstraction, these manipulations may be offered at the level of graphical objects that can be created, deleted, displaced or otherwise adapted to fit the user's mental picture. In physics-aware model environments, e.g. where several objects may not fill the very same spot, this kind of interaction defines the need for the integration of a physics engine. A comprehensive overview of the taxonomy of the vast field of physics simulation is provided by [19]. However, in the scope of this paper, we focus on real-time methods of forward dynamics, considering three categories: rigid body dynamics [20, 21], deformable body dynamics [22], and particle-based fluid dynamics [23].

At the very foundation, the general laws of motion drive physics engines. Non-penetration constraints, collision resolution and friction forces, and complementary constraints round off the field of rigid body simulation. For calculating the respective forces, various approaches exist, e.g. the penalty force method, Lagrange multipliers, impulse-based simulation, and reduced coordinate formulation. Systematically removing degrees of freedom among model components by introduction of constraints, one can define mechanical joints between rigid bodies. Model constructs that are comprised of a multitude of joined links are referred to as articulated bodies [24].

Deformable bodies can be understood as yet another extension of articulated bodies in the sense that the nodes of a physics representing mesh are all intertwined. An overview of traditional modeling approaches to deformable bodies in an animation context can be found in [25]. Diziol et al. presented an approach to computing incompressible deformable mesh dynamics that is superior to previous real-time approaches in terms of efficiency and accuracy [22]. In addition to various optimisation steps, this approach benefits from the simplifying idea of inferring the effecting forces on individual nodes of the physics mesh from the differences to the original shape of the surface.

Fluids can be computed at interactive speeds relying on the smoothed particle hydrodynamics model [23]. Here, fluid dynamics emerge from the idea that a large quantity of particles interact. The local neighbourhood of each particle determines its individual, virtual density. Differences in density among neighbouring particles result in pressure, which in turn motivates the particles' acceleration and velocity. Recently, a particle-based model was published that promises a unified approach to multi-physics in real-time [26].

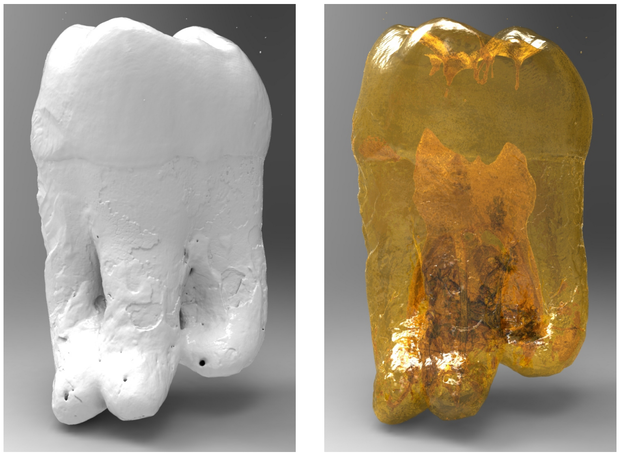
TOWARDS MULTI-PHYSICS REPRESENTATION WITH RIGID & RIGGED BODIES

For our first demonstrator of virtual root canal treatment simulation, we make extensive use of the broadly established methods of rigid body physics calculation. We use it in two different ways. (a) To cope with drilling, shaping, filing of hard dentin material. And (b), to trace the deformation of flexible dental files to unearth insights about their interactions in the root canal system. Before detailing both of these aspects, we outline the general interaction scenario of our virtual endodontics simulation.

Interaction Scenario

The asset base of our simulation is comprised of a representation of the tooth-root complex and the dental instruments being used to treat it. The tooth data (Figure 1) has been provided from experienced researchers in the field of computer tomographic imagery. It was captured by means of a Micro-CT scanner and achieved a spatial resolution of about 20 µm. Mesh surfaces are extracted from the volumetric data using the Marching Cubes algorithm in order to render the tooth in an interactive display. Initially great numbers of vertices (roughly 700.000 in the displayed case) can be reduced to about 100.000 using standard mesh decimation techniques without loosing crucial morphological or structural information.

Figure 2 shows some of the instruments needed to perform endodontic therapy. We recreated these tools in a



(a) (b)

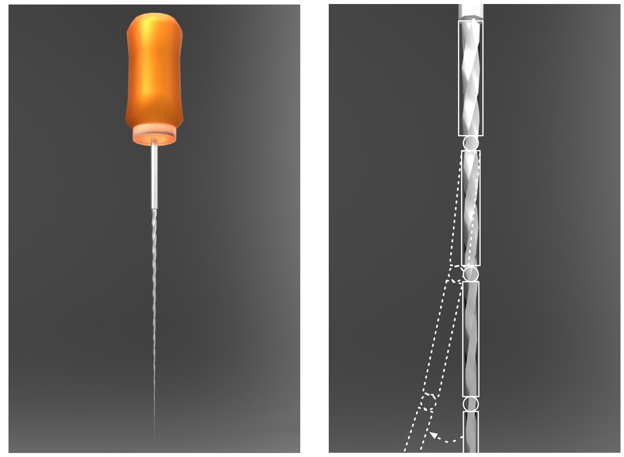
Figure 1. ISO Surfaces extracted from volumetric CT data of a molar. (a) An opaque material emphasises the coarseness of the surface structure. (b) A transparent material reveals the morphology of the internal root canals.

3D modelling application. Towards this end, a simple two-dimensional shape that retraces the cross-section of the tool tip is laid out, segments of its extruded volume are aligned on top of each other and deformed using twist, skew and proportional scaling modifiers. Figure 3(a) displays an according three-dimensional model.

Figure 2. From top to bottom: Two files that are manually operated to remove infected pulp tissue as well as one bur that works with a motor-driven handpiece.

Drilling, Shaping & Filing

As shown in preceding works on virtual dental training, the volumetric tooth data informs the physical interactions with dental instruments [27]. In order to speed up the physics calculations, we focus on improving the detection of collisions between instruments and the tooth matter. Distance fields provide the core technology for our implementation [28]. Here, the distance field information tells us how far away from a dentin or pulp tissue surface the dental instrument is, or alternatively, how far it has penetrated the according substance. The distance field also provides an efficient data structure to calculate the contact normal as well as the speed of the incident. A penetration event can only occur, if an according force was applied [29]. In order for the user to adjust the applied force appropriately, he might work with one of the aforementioned force-feedback devices or react to corresponding visual cues [30]. In case a sufficiently



(a) (b)

Figure 3. The 3D model of an endodontic file. (a) The handle and the geometry built from the cross-section of the instrument's tip. (b) A conceptual display of the instrument's physical representation as a rigged body—stress is propagated along an array of box colliders linked by socket joints.

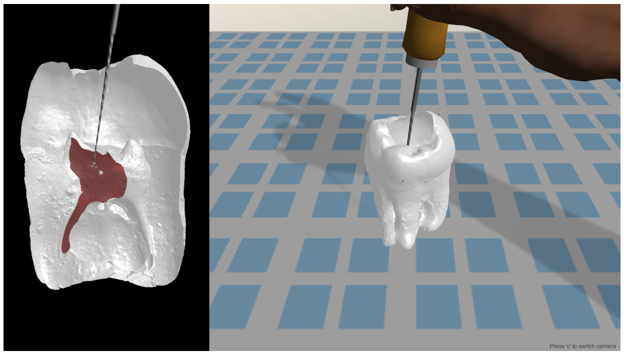
great force is applied, we remove the intersecting area from the uniform voxel grid and we update the local distance values. The distance field is generated following the concept of level-set segmentation which ensures that the irregularities of the geometry of the tooth, i.e. bumps and concavities, are considered but scalable patterns are efficiently and parametrically represented [31]. Next, the level-set segmentation is translated into the distance field for the tooth and efficiently used for testing and resolving collisions [32]. There is also a GPU-based implementation for this approach [33].

Tracing File Deformation

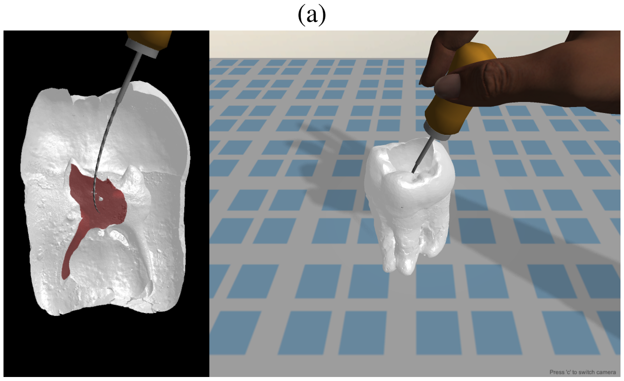
For preparing access cavities, as has been the usual goal for computer-based endodontics simulation so far, manipulating the dentin voxel volume is the target of any physical interaction. However, especially in case of cleaning the root canals, it is essential to also consider the impact of the physical interactions on the dental instruments. For our first demonstrator, we approached this challenge by fitting an array of box colliders around the endodontic files with a joint connecting each collider to its neighbour (Figure 3(b)). The spring dampening coefficient of the joints define the overall body's reactive stiffness, whereas a steady force is working on each link to recover the original shape. This recovery force considers the file material, the angular deviation at the joints and it points towards the central axis of the file. Screenshots that visualise this interaction from within our simulation are presented in Figure 4.

DISCUSSION

The effectiveness of our current demonstrator has been confirmed by the domain expert on our team as well as by closely collaborating university researchers in endodontics. Its hardware setup features an Oculus DK2 head-mounted display and a LeapMotion finger tracking sensor. In order to increase its accessibility, we need to make it less dependant on special hardware and desktop PCs. Instead, we are in the process



(a)



(b)

Figure 4. Screenshots from within our simulation environment. (a) The endodontic file penetrates soft pulp tissue. (b) The file grinds against the root canal and bends as a result.

of developing a head-mounted VR solution based on ZEISS VR One or Samsung Gear VR, which feature top-of-the-line smart phones and tablets for computing and visualising.

In this light, due to the comparably low processing power of mobile devices, the efficient calculations of the presented approach based on distance field-based collision detection and joint-based deformation are all the more important. However, our concept suffers from certain drawbacks. The greatest ones are the lack of fluid simulation and the strong limitation of the deformable dynamics implementation. The latter works great for simulating the flexibility of the dental tools. However, it does not suffice to simulate deformations of pulp tissue. As the scraped off tissue sometimes needs to be flushed out, fluid simulations are yet another important aspect that we have not considered, yet.

Our aim for the next demonstrator is to translate our models into a particle-based representation similar to [26]. For this to happen, we will segment the volume data of the tooth into its different structures, and then manually classify their material properties. We will then use a surface reconstruction algorithm (Marching Cubes [34] or Dual-Contouring [35]) to generate the surface particles. To generate particles beneath the surface, within the volume of a tooth structure, we simply generate particles for each sample-point on a uniform grid. For soft-bodies we can use the density information from the volume data to parameterise the softness of the particles.

CONCLUSION & FUTURE WORK

Based on seminal dental research literature, we motivated the need for understanding root canal morphology. We presented an approach to address this challenge by augmenting the information typically available in a dental clinic in a virtual training environment. Based on expert feedback, we determined that such augmentation has to happen in the context of the procedural steps that would be performed during clinical therapy. In contrast to preceding virtual dental training simulators, we understand that only a mature multi-physics approach can allow for the expected rich set of interaction dynamics. We have taken the first steps towards this goal, integrating rigid and deformable body dynamics for the targeted application domain. In order to allow for richer calculations, we introduced a level-set-based method to the domain for fast collision detection using signed distance fields. In order to address the need for deformable body physics, which is essential in endodontic simulation, we introduced an efficient, if specialised, method to simulating flexible dental files. In particular, we provided a rigged body structure aligning several box colliders along the geometry of the file. The discussion revealed that our approach still has certain drawbacks. Yet, at the same time, we have already outlined a plausible path to generalise the presented deformable body concept and to introduce and couple the existing physics representations to fluid mechanics.

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