Interactive Simulation of Tooth Cleaning
with an Interdental Brush

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Proper cleaning of tooth interspaces is significant to sufficient caries prophylaxis. In this article we present a system for the simulation of this cleaning procedure using an interdental brush. Various application areas for the simulation are presented and the purpose of our work is explained. Simulation methods are shown, including data acquisition and preprocessing, an editor for the design of simulated interdental brushes and the mathematical methods on which the simulation of flexible parts of the brush is based. The presentation of the haptic user interface and a glance on the overall simulation system complete the chapter on methods. Afterwards we show first results of our work, and the article ends with a conclusion and a view on further work to be done in future.

1 Introduction and purpose of the work

Tooth cleaning is a very important contribution to caries prophylaxis. The tooth cleaning process refers to brushing the teeth and purging the interspaces between them. Cleaning of the teeth is mostly done with a toothbrush while more sophisticated equipment is needed for sufficient cleaning of the interspaces. Interdental brushes, for example, allow close and facile cleaning of the teeth’s interspaces.

In our paper we present an approach for the simulation of tooth interspace cleaning using an interdental brush. This simulation system offers some advantages to dentists and their patients. Dentists are able to simulate the general behaviour of an interdental brush as well as the cleaning performance achieved with certain brushes or different cleaning strategies. Due to the application of a haptic user interface it is even possible to record the cleaning pattern of a proband and to analyse different cleaning techniques in order to optimise caries prophylaxis.

Benefit is also granted to the manufacturers of interdental brushes. The simulation system enables early tests of the functionality of future brush generations and enables the engineers to estimate the effects of design changes in an early state of the manufacturing process. Furthermore, the simulation system offers a cheap way to experiment with different designs and functional properties in the development process of interdental
brushes. It also allows to validate the efficiency of certain brush types and to find out what has to be optimised in current design studies.

This paper presents the simulation system and the techniques on which the system is based. In section 2 the methods for the realisation of the system are described. First, data acquisition for jaw and brush models is described and the different preprocessing techniques for the model generation are shown. Then, the editor for computer based generation of different brush models is presented. Afterwards, we present the mathematical method for modelling of flexible parts of an interdental brush. In the following part of the method section the software modules for realistic simulation of the brushes’ behaviour are described. In the next paragraph we introduce the haptic based user interface. Finally, we show the combination of the single modules into a complex and powerful simulation system. In section 3 first results of our work are shown. The paper is finished with a conclusion and a view on further work to be done in future.

2 Methods

2.1 Data acquisition and preprocessing

For a realistic simulation of the tooth interspace cleaning process three-dimensional models of the interdental brush and of the bit to purge are needed. In figure 1 an interdental brush holder with a traditional brush can be seen.

Concerning the brushes, we consider only such devices with toothbrush-like brush heads in our simulation. CAD models of different handles were provided by our industrial partner. As the simulation is based on the Open Inventor [1] data format, we have to convert the models into the Inventor data type. This task is done with help of a ProEngineer CAD system. It is very important to maintain the exact shape of a handle as the handle concludes the function of a lever. The contact points of the human fingers influence the forces that act on the bristles and by means of the bristles on the teeth and their interspaces. Flexible areas of the handle, which can be bent, are modelled using the Finite Element Method [2] [3].

The bristles are not modelled in CAD for their simple shape which makes it easy to fabricate them. As the bristles offer a very elastic behaviour, a Finite Element approach is used to model their mechanical properties. Further information on the Finite Element modelling process of the bristles and the flexible parts of the handle is given in section 2.3.

Bit models for the simulation, consisting of upper and lower jaw, are generated out of two different data sources. On the one hand, plaster cast models of FRASACO standard jaws are used for this process. These normalised cast models offer a fixed shape and can be maintained in medical speciality shops. The plaster casts are scanned using a CT device which results in a collection of CT slice images. On the other hand we use CT scans of the upper and lower jaw of individual probands for our simulation system.
The generation of Open Inventor models out of the CT images requires several data conversion tools. The raw data slices of the CT scans are anonymised and converted to a more sophisticated data format. In the next step the slices may be cropped and filtered. At last a set of polygons is created out of the slice images which can easily be converted into an Open Inventor file. As the scanning of plaster casts with a CT device results in a quite bad resolution, we are currently thinking about better solutions. One possibility could be the scanning of the models with a laser scanner which has already been tried by other research groups [4].

For convenient visualisation of the resulting Open Inventor models we have implemented a visualisation tool based on the natural Open Inventor Visualiser gview. In figure 2 models of a lower jaw derived from a plaster cast and of an interdental brush can be seen.

Figure 2: Open Inventor models of a jaw and an interdental brush

2.2 Interdental brush editor

For convenient design of different interdental brush types, a brush editor has been developed. This editor allows the user to constitute design, structure and material properties of a brush. An interdental brush is made out of four different parts: Stiff handle area, flexible handle area, single bristle and bristle bundles. Each of the four constituents can be parameterised in various ways. As an example, a closer look on the bristle design is taken in this paragraph.

When calling the bristle editor, which is a subprogram of the interdental brush editor, the first step is to choose a general bristle type. It is possible to view the Open Inventor models of the different bristle types and additionally a set of parameters belonging to each bristle type can be specified via a graphical user interface. Figure 3 shows the main window of the bristle editor and the parameter configuration window. Editors for the other parts of an interdental brush have been realised in the same way.
2.3 Modelling of flexible areas and bristles

For the modelling of flexible behaviour, which can be found with bristles or with the dynamic part of a brush handle, a basic Finite Element model is used. First the flexible area is divided into equidistant elements. Then, each of these elements is modelled as a member. Figure 5 shows a member which is fixed at one end. In the left part of the image, the effect of a force applied to the member can be seen while the right part shows the effect of a momentum.

For each member with length $l$ the dynamic behaviour is given by the following equation [3]:

$$\Pi = \frac{1}{2} EI \int_0^l \omega''(x)^2 \, dx - \sum_{i=1}^{m} F_i \omega_i - M_i \omega_i'$$

which can be written as a differential equation like this:

$$\omega'' = -\frac{M(x)}{2EI}$$

The analytical solution of this differential equation for a single one of the equidistant elements is given by a polynomial function. Taking this polynomial as an approach for the solution of the problem within the Finite Element Method, it provides precise function values for the contact points between the different equidistant elements.

A single bristle is currently modelled by five equidistant members. Due to the dependencies between adjacent members, a $10 \times 10$ matrix $A$, containing the single polynomial equations, represents the Finite Element model for a bristle. Considering additional conditions to be fulfilled by the equations, the resulting matrix $A$ contains many zero values. The following equation represents the solution of the Finite Element calculation for a bristle

$$A \ast x = b$$

$b$ is a 10 dimensional vector that specifies the forces and momentums on each member, and $x$ determines the new position and angle values of the member elements after application of the forces and momentums. As the matrix $A$ contains many zero values, the calculation of the vector $x$ is not very complicated. Mathematical formulations equivalent to that described above have been taken for the Finite Element modelling of the flexible handle area.
2.4 Brush simulator

For the visualisation of the simulated cleaning process we use the KArlsuher VISualiser [5]. KAVIS has been developed at our institute using the Open Inventor toolkit. It is a powerful simulation and visualisation package, in which Open Inventor data sets can be extended by adding joints between different geometrical objects. Afterwards, dynamic behaviour can be simulated using KAVIS functions. For this work we extended KAVIS with the ability to simulate tooth interspace cleaning. Dynamic behaviour of the brush data sets is achieved using the mathematical formulations described in the previous paragraph. In the following figure a screenshot of our bristle movement simulation can be seen.

![Bending bristle, as is and hidden line draw style](image)

2.5 Haptic user interface

A more realistic behaviour of a simulation system can be achieved using an adequate user machine interface. For our work, we integrated a PHANToM device [6] in our simulation system. Force-feedback can easily be simulated by programming a force field using the GHOST library [7] delivered with the device. The force-feedback device plays the role of a virtual interdental brush. It is also possible to mount a real brush on the PHANToM and to clean a plaster cast with it. Calibration and tracking of an interdental brush using the PHANToM have been implemented. For the tracking feature a mode called Multitrack allows to switch between the view of the interdental brush, the view of a simulated PHANToM with the brush or the view of the trajectory reached by the interdental brush. Furthermore, a simulation of the PHANToM´s overall functionality is available. Figure 6 shows a PHANToM with a calibration unit and the KAVIS simulation of this device.
2.6 The complete system

The system for the simulation of tooth interspace cleaning has been built using the single components described above. Additionally, a graphical user interface is available for user guidance. Figure 7 shows the interaction between the KAVIS library and the haptic user interface.

3 Results

A first prototype of our system has been established, using a SGI Octane SSI with a single R10000 processor, together with a 1.5A PHANToM device of SensAble Technologies Inc. The software modules described above have been implemented and form a powerful simulation application. It is possible to simulate the movements of an interdental brush considering the concrete material properties specified by the user. Reaction on surface contact and especially on tooth interspace touch is simulated quite realistically. The simulation is haptically supported, all user movements can be tracked and analysed afterwards. First results are promising and we will soon do a test run with probands at our university. Figure 8 shows a screenshot of our KAVIS based simulation system.

4 Conclusion
In this paper a 3D graphical simulation system for visualisation and analysis of tooth interspace cleaning has been presented. The system is based on the Open Inventor data format and on the KAVIS simulation package, which is an extension of the Open Inventor toolkit. In the system, standard jaw data sets may be used as well as patient individual data. Interdental brushes are modelled using original CAD data and self-made bristle models. Behaviour of flexible elements of the brushes like the bristles of parts of the handle are modelled using the Finite Element Method. The human machine interface of the system combines a haptic device with a graphical user interface. First results are promising and the system will be refined.

Future work will concentrate on collision detection for the interdental brush and the teeth. Moreover, we will implement a reachability analysis for the brush and especially the bristles in order to control which points in the oral space are touched by the brush. This feature may easily be combined with a risk model developed in our group [8] in order to mark certain areas which should be cleaned anyway or which must not be cleaned at all. First clinical tests are scheduled in the year 2000.

Possible enhancements of the project include also the integration of this work into a pre-operative planning system for cranio-facial surgery [9] or the combination of this work with an experimental setup for intraoperative support of surgeons [10].

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References