Physics-based burr haptic simulation: tuning and evaluation

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Abstract

In this paper we provide a preliminary report on our work on the tuning of a temporal bone surgical simulator using parameter values derived from experimental measurements, and on the comparison between these results and the previously used "domain expert" assigned values. Our preliminary results indicate that the parameter values defined by the domain-experts are consistent with the experimentally derived values. Psychophysical testing indicates that the simulator is capable of rendering the basic material differences required for bone burring work and that some trained users preferentially associate a simulated temporal bone resin model with its real counterpart.

1. Introduction

The dynamic response of virtual reality surgical simulators is often controlled by physical models that are designed to capture the essential features of the anatomy, tissues and surgical tools involved. Given the real–time requirements imposed by this class of applications, and the current capabilities of hardware, these models are, usually, the result of a rather drastic simplification of the specific bio-mechanics involved, with their behavior controlled by a set of parameters that lump together details that would be otherwise uncomputable. The parameter set is then tuned to be consistent with the experience of surgeons proficient in the specific surgical procedure being simulated. Given the difficulties connected to direct *in-vivo* measurements, this is, usually, the only approach that can be followed; even though there has been significant recent progress in the development of instrumentation capable of direct, *in-vivo*, measurements of the biomechanical characteristics of soft tissues see, for instance, [5, 7, 10].

It remains, however, an interesting question if these two approaches to parameter definition are actually compatible and, more specifically, given the limitations introduced by the computational algorithms and the devices used for haptic rendering, how much of the detail that can be obtained from direct physical measures will actually be usefully perceived by the user.

Here we provide a preliminary report on our work on the tuning of a temporal bone surgical simulator[1] using parameter values derived from experimental measurements, and on the comparison between these results and the previously used, "domain expert" assigned, values. Specifically, we are interested in understanding: if the domain-expert assigned parameter values – used to control the behavior of our bone-burring model in [3, 4] – are consistent with what could be obtained from experimental measurements; and how sensitive are humans to changes of parameters close to the selected reference value.

Our preliminary results indicate that the parameters value derived from expert surgeon experience are consistent with the experimentally derived ones, and that, within the visual and haptic rendering capabilities of our temporal bone surgery simulator, humans are not able to differentiate between experimentally close, but distinguishable, materials such as human petrous bone and Pettigrew Plastic Temporal Bones [13]. Pettigrew models are widely used in surgical training as a valid alternative to cadaveric exercises.

The rest of the paper is organized as follows. After a brief description of the clinical context, we summarize in section 3 the bone-burr interaction model[4] used in the simulator. The following section describes our experimental setup and how we use the experimental data to set the parameters controlling the simulator. Section 5 illustrates the psychophysical experiments we have performed thus far and their results. The paper concludes with a discussion of the results obtained and a view of current and future work.

2. Virtual temporal bone surgery

The temporal bone is one of the most complicated anatomical areas in the human body [12]. Surgical accessibility of all of its structures has vastly increased the number of potential treatments for patients with hearing or balance disorders. Successful execution of temporal bone dissection requires a high level of dexterity, experience and knowledge of the patient anatomy. Human cadaver dissections are currently considered the primary teaching tool. However, this training method is made increasingly problematic by the physical limitations and decreasing availability of the material, its high handling and disposal cost, as well as the risks associated to transmission of diseases such as BSE. A VR simulator convincingly mimicking a patient-specific operating environment ought therefore contribute significantly to the improvement of surgical training.

Figure 1. Surgical equipment vs Simulator setup: In a real surgical environment, the surgeon keeps in his hands a high–speed rotating burr and a sucker and looks through a microscope. The current simulator configuration provides haptic feedback by two PHANToM haptics devices, and visual feedback by a binocular display.

Accurate and fast burr–bone interaction simulation is a key enabling technology in the development of such a simulator. It has to include burr–bone contact detection, bone erosion, generation of haptic response, and synthesis of secondary visual effects, such as bone debris accumulation, bleeding, irrigation, and suction [1]. The human perceptual requirements of a simulator impose very stringent constraints on performance, making bone dissection simulation a technological challenging task.

A number of groups are developing simulators for bone dissection. Early systems (e.g. [8]) focused on increasing the understanding of the anatomy by providing specialized visualization tools of static models. The Ohio Virtual Temporal Bone Dissection simulator [20, 6, 18], and the VOXEL-MAN system [14, 15], similarly to our work, aims instead at realistically mimicking the visual and haptics effects of a real operation. Our work is characterized by a physics-based contact model, the use of patient specific data, and its focus on validating the haptic model with experimental data.

Our surgical simulator has been designed following the requirements identified in a human factor analysis[9, 2]. The current simulator configuration provides haptic feedback by two PHANToM haptics devices, and visual feedback by a binocular display(see figure 1). We resolve the difference in complexity and frequency requirements of the visual and haptic simulations by modeling the system as a collection of loosely coupled concurrent components. The haptic component exploits a multi-resolution representation of the first two moments of the bone density to rapidly compute contact forces and determine bone erosion.

The visual component uses a time-critical particle system evolution method to simulate secondary visual effects, such as bone debris accumulation, bleeding, irrigation, and suction. The system runs on two interconnected multiprocessor machines. The data is initially replicated on the two machines. The first is dedicated to the high-frequency tasks: haptic device handling and bone removal simulation, which run at 1 KHz. The second runs concurrently at about 15–20 Hz, the low-frequency tasks: bone removal, fluid evolution and visual feedback.

The two machines are synchronized using one-way message passing via the Stanford VRPN library[16]. The Virtual-Reality Peripheral Network (VRPN) system provides a device-independent and network-transparent interface to virtual-reality peripherals. This communication library also provides a suitable means to record complete traces of the training sessions, which can then be processed off-line by data analysis tools.

3. Burr–bone interaction and haptic feedback

A detailed mechanical description of the cutting of material by a rotating burr is complicated because it involves: the tracking of the continuously changing free surface of the material being cut; the impact of the burr blades on the surface; the resulting stress distribution in the material; and the consequent plastic deformation and break–up. In the general engineering context these problems are solved by using experimentally determined characteristic curves, but, for the specific case of bone burring, there are no publicly available data. Furthermore, in the specific context of haptic feedback, one cannot apply the standard methods found in the mechanical engineering literature for the simulation of milling. In fact, a haptic feedback system is driven by an open–loop controller that needs to rapidly evaluate a reasonable response force for arbitrary tool penetrations.

To circumvent these complications, we have developed a simplified model, originally described in [3], based on a limited number of parameters that were, thus far, tuned by trial and error following the opinion of expert surgeons.

3.1. Elastic force

The basic assumption underlying our model is that the burr bit is moving relatively slowly with respect to the time scale of the haptic feedback loop and that one can estimate the elastic forces exerted within the bone by geometrically characterizing the region of bone intersected by an idealized sphere representing the burr tip.

Specifically, we model the burr bit, B, with a sphere of radius R centered at $\mathbf{R}_b$, and consider the first two moments of the bone mass density, $\rho(\mathbf{r})$, contained in B.

$$m_0 = \int_{r<R} dr^3 \rho(\mathbf{r}), \mathbf{m}_1 = \int_{r<R} dr^3 \rho(\mathbf{r})\mathbf{r}. \quad (1)$$

The direction of the local normal, $\hat{\mathbf{n}}$, to the bone surface can then be estimated as $\hat{\mathbf{n}} = -\mathbf{m}_1/|m_1|$, and from the amount of mass contained in B, m_0, we can derive an effective "penetration depth" h as the smallest positive solution of

$$m_0 = \pi \rho_0 R^3 (\frac{h}{R})^2 (1 - \frac{h}{3R}) \quad (2)$$

where ρ_0 is the "solid" bone reference density.

We can now write an expression for an effective force $\mathbf{F}_e$, that is intended to model the elastic response of the bone to the impinging burr.

$$\mathbf{F}_e = c_e R^2 (h/R)^{3/2} \hat{\mathbf{n}}, \quad (3)$$

where c_e is a dimensional constant, that, as far as this model is concerned, describes the elastic properties of the material. In the limit of $h/R << 1$, eq. (3) is consistent with Hertz's contact theory [11].

Typical burr radii are between 1 mm and 5 mm, while the typical speed at which the burr bit is moved is $<$ 100 mm/s [1]. Given that the haptic device acquisition period is 1 ms, the burr bit will typically move a distance of the order of a few percent of its radius. Therefore, it is reasonable to compute interaction forces by checking collisions after the fact, rather than trying to predict them in advance.

3.2. Erosion

Erosion, i.e. material removal in response to burring, is modeled as a position dependent erosion rate described by f, an erosion shape function,

$$\frac{d\rho(\mathbf{r})}{dt} = \alpha f(r/R) \rho(\mathbf{r}); \quad (4)$$

where, again, $\mathbf{r}$ is measured from the center of B, and all relevant detail on the burr bit cutting characteristics, angular velocity, and so on are lumped together in the dimensional constant α. The shape function f is constrained to have a maximum at $r/R = 0$ and to be null for $r/R > 1$.

From an implementation point of view, our model the bone is described as a collection of voxels, each one containing up to 255 levels of bone occupation. To accommodate for a wide range of erosion rates using only 8 bits, we convert the rate of erosion given in Eq. (4) to a probability that the value of the voxel at position $\mathbf{r}$ will be reduced by one at next time step. A Russian roulette scheme is then used for deciding whether to fully erode a bit (i.e. remove 1/255th of the mass of a full voxel) or not.

In [4] we have shown that by using a multi–scale spatial description it is possible to evaluate eq. 3 and eq. 4, even at the largest burr radius (5mm), well within the time constraints imposed by the force–feedback loop.

4. Fitting the bone burring model to experimental data

The model described by eq. 3 and eq. 4 is, undoubtedly, over-simplistic being mainly motivated by practical computational reasons. Its behavior is controlled by two constants, c_e and α whose value should be determined by the material modeled.

While in [3, 1] we tuned these constants to be consistent with the subjective surgeons experience, here we try to define a value for them based on direct experimental measures. Specifically, we have selected a simple reference experiment, the vertical descent – at constant applied force – of a burr into the material, that we perform both in a real experimental set-up and its virtual analogue. Under the assumption that our simplified model captures some of the main features of the real system, we then fix the parameters of the virtual model by a non–linear fit of the simulated to the experimental data.

We perform this procedure to fit to human petrous bone data, Pettigrew Plastic Temporal Bones [13] a synthetic resin model of the temporal bone widely used in surgical training, and, for reference purposes, PVC K70 resin.

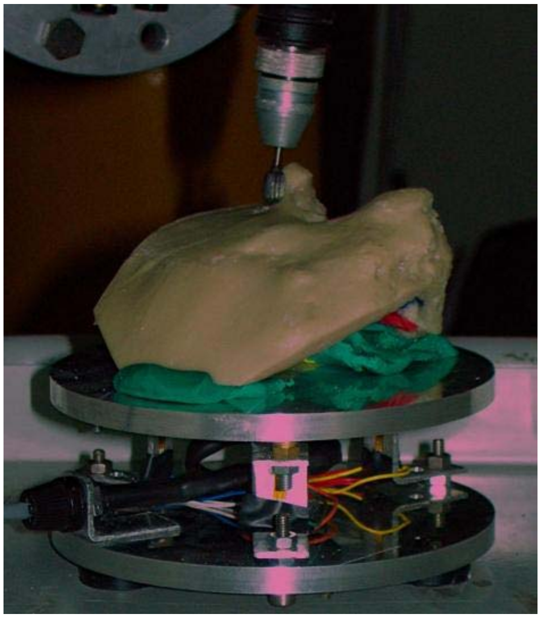

Figure 2. Experimental setup: a robot arm equipped with a high-velocity burr, moves along the vertical direction, while a load cell records contact forces to feed a velocity loop controller.

4.1. Experimental setup

In order to derive characteristic parameters for our virtual simplified model of the contact actions between cutting burr and bone material, we developed and built a measurement facility. This experimental system may record contact forces between burr and material during controlled movements, and it contains the following items:

- an arm robot in composite material with three degrees of freedom, capable of controlled movements with a precision under $10\mu m$;
- a mini drill MINICRAFT, model MB150, commonly used for surgical training, mounting a 6mm diameter spherical burr, and running at 30,000 rpm
- a mono–directional load cell, obtained by instrumenting an aluminum platform with strain–gauge sensors.

Figure 2 shows the experimental system in action, with the burring tool moving against the sample, and evidentiates the aluminum load cell.

The burr is moved vertically by the robot arm, with the robot arm vertical velocity controlled by a feedback control system [19, 17] that aims to maintain the vertical force felt by the load cell to a predefined value.

The same control algorithm is used to drive an analogue experiment performed by the virtual system. Figure 3 shows the difference between the real experimental control system, and the virtual one, where the real arm–burr–bone system is substituted by the simulated model.

The experimental sessions begin by applying a constant force along the rotating tool axis, and by measuring and recording the tool positions. The vertical run of the burr is stopped when the burr bit is immersed by about one third of its radius. Experimental data are then compared with simulated data obtained by measuring burr displacement when the virtual movement of the burr is controlled by a constant force applied to the model described in section 3.

In figure 4 we show a plot of the typical force, position and velocity measurements done during a run in PVC. After the impact of the burr on the material, the burr proceeds at an essentially constant velocity until it is well inside (more that one third of its radius) the material volume. We will use this velocity, see next subsection, to characterize the behavior of the material at that level of applied force.

4.2. Experimental results

In figure 5 we report our preliminary measurements of the initial penetration velocity of the burr on the mastoid region of a human temporal bone sample for different levels of applied constant forces. Our data shows a certain amount of scatter, due to the inhomogeneous nature of the material, but, nevertheless, seems to indicate a well definite trend when the applied force is increased.

The solid line plotted in the same figure represents the data generated by the analogue virtual experiment with parameters, $c_e = 2.145$ and $\alpha = 0.087$, fitted to minimize the sum of the squares of the differences between the measured and the virtual penetration velocities at the same level of applied force. Since the selection of the parameters is the result of the non-linear fitting to procedurally generated data, we were not able to derive direct estimates of the confidence interval for the fitted parameters. As an indicative measure of the latter, we show, as dotted lines, the curves corresponding to erosion values $\alpha = 0.077$ and $\alpha = 0.097$.

In figure 6 we report our preliminary measurements of the initial penetration velocity of the burr on samples of Pettigrew Plastic Temporal Bones [13]. Again, as in the case of the real temporal bone there is scatter in the data due to inhomogeneities in the sample. The solid line is, as above, the result of a non–linear fitting and it corresponds to $c_e = 1.504$ and $\alpha = 0.116$. The dotted lines correspond to erosion values $\alpha = 0.106$ and $\alpha = 0.126$.

As a reference, we acquired homologous data for PVC K70 resin. These resulted in parameter values $c_e = 0.462$ and $\alpha = 0.256$.

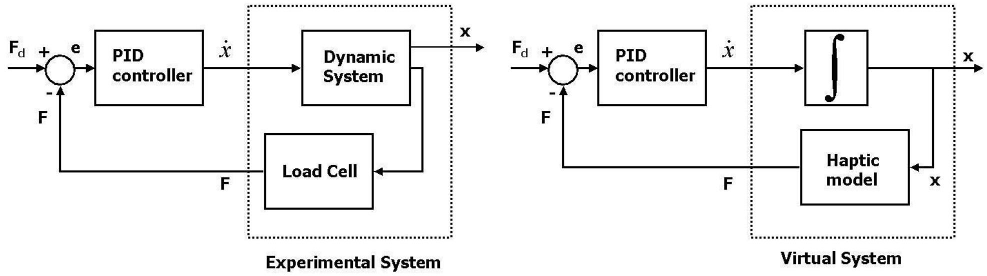

Figure 3. Real Control System vs Virtual Control System: the same PID controller and the same kind of force-feedback control is applied to the real system, and to the theoretical model, in order to compare the results.

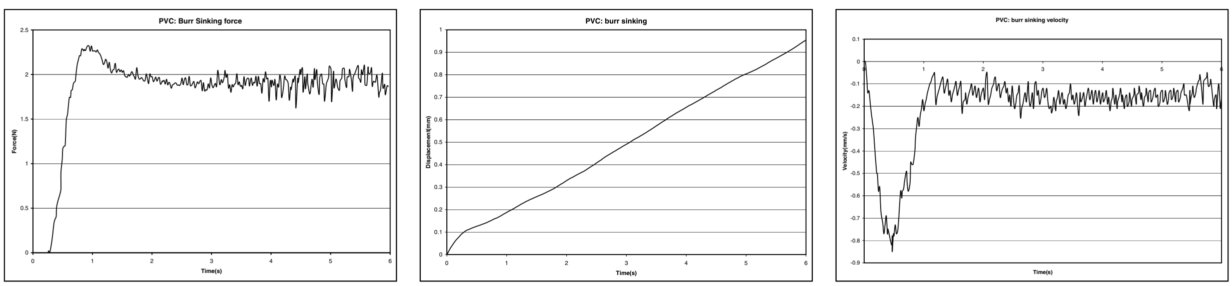

Figure 4. Typical force, position and velocity plots recorded by our experimental system while burring on a block of PVC. Note the impact of the burr on the material and the velocity stabilization at time 1s.

Notably, the expert selected values we have previously used, $c_e = 1.5$ and $\alpha_{er} = 0.1$, are consistent with the values measured for the actual temporal bone and the Pettigrew Bone result. See, however, the results of the following section.

5. Psychophysical experiments

In order to evaluate the feel of the simulator in an objective manner we performed a series of psychophysical experiments. In this section we present their preliminary results.

5.1. Differentiating between virtual materials

Experts can feel the difference between real PVC and bone and the same subjective ability ought also apply to users of our simulator. In particular, two different tactile cues are known to be used in distinguishing real materials: (1) the tactile feedback received when probing a material's surface; (2) the burring effect received when drilling through it. We investigated whether users could distinguish between simulated PVC and simulated bone using either of these two perceptual cues. We selected 20 volunteer subjects with no previous experience with the simulator. After an initial phase of familiarization with the simulator, each subject was exposed to two sequences of 12 trials. In the first sequence of trials the subject was asked to simply probe the surface with the drill, while in the second sequence they were asked to drill into the interior of the material. A 2AFC design was followed whereby each trial is divided into two equal 20s intervals. In each interval the simulator rendered one of the two chosen material samples A or B. The subject's task was to indicate whether the material felt the same or different. The simulator was programmed to present samples in a random sequence while achieving an equal num-

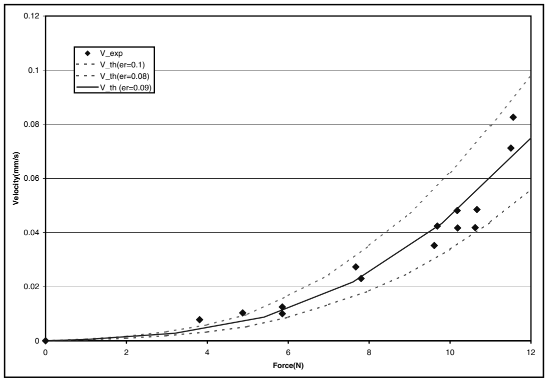

Figure 5. Haptic model fitting with bone experimental data: square points represent the experimental initial sinking velocities of the burr on the mastoid region of a human temporal bone sample for different levels of applied constant forces. The solid line represents the data generated by the virtual analogue experiment with parameters fitted, while the dotted lines provide an indicative measure of the confidence interval on the erosion factor parameter($\alpha = 0.077$ and $\alpha = 0.097$).

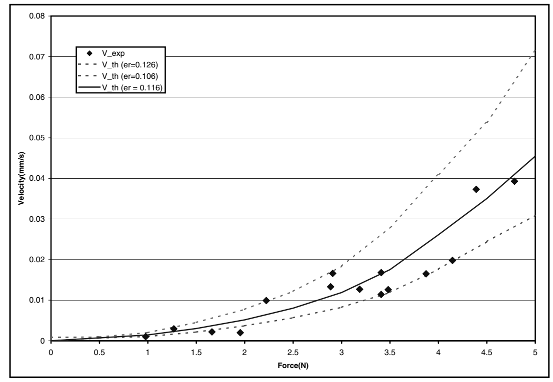

Figure 6. Haptic model fitting with Pettigrew plastic temporal bone experimental data: square points represent the experimental initial sinking velocities of the burr on a Pettigrew plastic temporal bone sample for different levels of applied constant forces. The solid line represents the data generated by the virtual analogue experiment with parameters fitted, while the dotted lines provide an indicative measure of the confidence interval on the erosion factor parameter ($\alpha = 0.106$ and $\alpha = 0.126$).

ber of trials presenting the four sample pairs: AA, AB, BA, BB. The response of each subject to each test was recorded. The mean scores (out of 12) over all 20 subjects were as follows:

1. Probing surface: 9.3 +- 0.4
2. Drilling material: 9.6 +- 0.5

Both of these are significantly above chance response level (p=0.001). They correspond to about a 75% correct level with some individuals obtaining perfect results and others worse – see histograms below – as might be expected for a group of naive users. Clearly, our intention is that with further training most users would progress towards a near perfect score.

Fig. 7 histograms the results of the test. Note how our tester population divides itself between persons with different levels of ability.

As a comparison, we asked, using the same methodology described above, the best 12 subjects coming from the previous experiment to differentiate between the haptic simulation of Pettigrew temporal bone and real bone materials, see fig. 8. The data indicate that the volunteers were above chance performance but less capable of differentiating between these two materials.

5.2. Associating virtual to real materials

In order to investigate whether the simulator captures some of the physical attributes of the materials that are used by users to perceive a difference between them we conducted a final experiment. This attempted a direct comparison between a real bone milling and the simulated experience. Again a 2AFC design was employed to nullify potential response bias. Here the task was necessarily more complicated since the user had to “keep in mind” the feel of the real material while comparing it to one of two simulated samples. We found that naive users generally found this task too confusing to participate usefully. Thus we limited subjects to those that had participated in the previous experiment and therefore had a good grounding in the simulated material difference. Each trial comprised three separate intervals, with the last two lasting 10 seconds, while the length of the first was at subject’s discretion.

1. subjects burred the real sample of Pettigrew temporal bone
2. subjects used the simulator to burr sample A
3. subjects used the simulator to burr sample B.

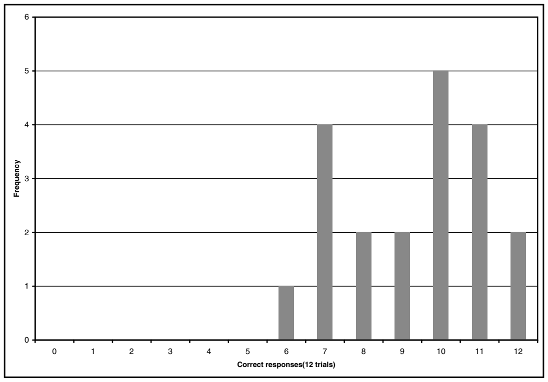

Figure 7. PVC vs Bone differentiation results: the histogram represents results of the psychophysical tests performed by haptic simulation of PVC and bone materials. The x axis represents the score of correct responses out of 12 trials while the y axis represents the number of subjects that totalized that score. In each interval the simulator rendered one of the two chosen material samples A or B. The subject's task was to indicate whether the material felt the same or different.

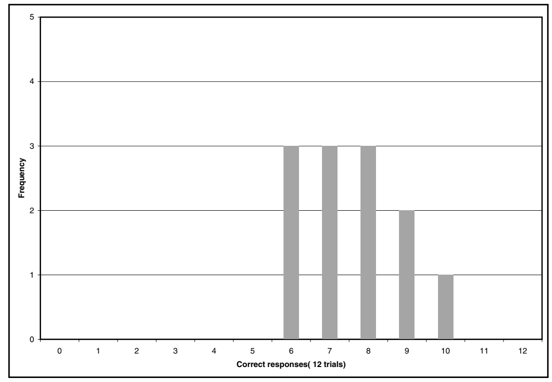

Figure 8. Pettigrew Temporal Bone vs Real Bone differentiation results: the histogram represents results of the psychophysical tests performed by haptic simulation of Pettigrew temporal bone and real bone materials. The x axis represents the score of correct responses out of 12 trials while the y axis represents the number of subjects that totalized that score. In each interval the simulator rendered one of the two chosen material samples A or B. The subject's task was to indicate whether the material felt the same or different.

The actual task was to say which of the simulated samples A or B felt most like the real sample. In each trial the simulated samples were PVC and Pettigrew temporal bone material but presented in random order. In all, five subjects each performed ten trials. The mean score (out of 10) over all 5 subjects was 9.4 +- 0.4. This is equivalent to 94% correct level and is clearly significantly above chance level ($p=0.0001$). This provides promising preliminary evidence that trained users are able to perceive the correspondence between real and simulated bone materials.

6. Conclusions and future work

Our preliminary results indicate that, within the limitations of our simplified bone–burr interaction model, we have consistency between domain-expert assigned parameter values and what could be obtained from experimental measurements. To put this result in perspective, we have then evaluated, via psychophysical testing, the simulator rendition of three virtual materials defined, respectively, by the parameters values for the mastoid region of human temporal bone, the Pettigrew resin model and PVC. Our preliminary psycophysical results indicate that subjects can easily differentiate between the virtual temporal bone and PVC while even the best between them cannot distinguish between the virtual models of the human temporal bone and the Pettigrew plastic one.

Finally, we attempted a direct comparison between the milling of a real Plastic Pettigrew model, and the simulated rendition of it and PVC. The results provide promising preliminary evidence that trained users are able to perceive the correspondence between real and simulated Plastic temporal bone material.

We are currently in the process of designing a set of more detailed psychophysical tests in order to establish further the correspondence between the burring of real and simulated materials.

Concurrently we are working on defining metrics appropriate to the performance analysis of complete training sessions.

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