Title:
A Computer-Aided Tool to Predict Dental Crown Prosthesis Surface Integrity after Milling

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Introduction:
Various pathologies (caries, fractures, fluorosis, and hypo-mineralization of enamel) lead to the rehabilitation of teeth with dental prostheses. Nowadays, prostheses can be manufactured from prefabricated biomaterial raw blocks, which are milled with a computer-aided design/computer-aided manufacturing (CAD/CAM) numerical chain [5]. The major challenge in restorative dentistry is to manufacture dental crown prostheses which are able to rehabilitate the tooth in order to fulfil functional performance and aesthetic requirements.

The milling process generates a characteristic signature on the prosthesis shape called surface integrity (SI) [3],[6],[7]. The residual SI after milling, not well understood in restorative dentistry, influences several requirements of the prosthesis surface such as aesthetics, biological response and mechanical behavior. Moreover, for each requirement, a specific SI might be manufactured in different anatomical area of the prosthesis. The concept of SI represents a new and preferential approach to characterize the surface and sub-surface properties regard to the functional requirement of prosthesis. SI analysis provides a comprehensive evaluation of the surface and its impact on the performance of the prosthesis [4]. The main difficulty for prosthesis manufacturers is to integrate the different expected SI during CAM process and particularly to choose the milling process parameters in accordance with prosthesis functionalities. The generation of a desired SI is still an iterative process based on experimental results capitalization. This inverse problem shall be addressed by a new approach focusing on the prediction of the milling process signature on the CAD model of the prosthesis shape. The concept of process signature, which aggregate information on surface modifications caused by the milling to which a material is subjected to, on different levels of scale, are a promising strategy to achieve a knowledge-based solution of the inverse SI problem [2]. This paper aims at providing a computer-aided tool to help prosthesis manufacturers to choose milling process parameters according to the expected SI after milling. Since roughness is a SI fundamental component of the prosthesis functionalities characterization, SI study is focused on roughness in this paper.

Material and Methods:
Prosthesis shape topological analysis
First, a topological analysis of 16 typical crown shapes is performed. This analysis is based on 3 axis milling constrains (Fig. 1a). When milling, the contact area (size and position) between the tool and the crown can change from it tip to it flank, and inversely, according to the prosthesis shape manufactured. These contact variations introduce residual roughness variations along the crown

shape. The contact simulation is implemented in Matlab software through a map of the tool/prosthesis contact (Fig. 1b) based on the STL model of the prosthesis. This contact map is implemented with a PLY format. According to the contact map the more representative contact surface types between the tool and the crown surface are highlighted (Fig.1c).

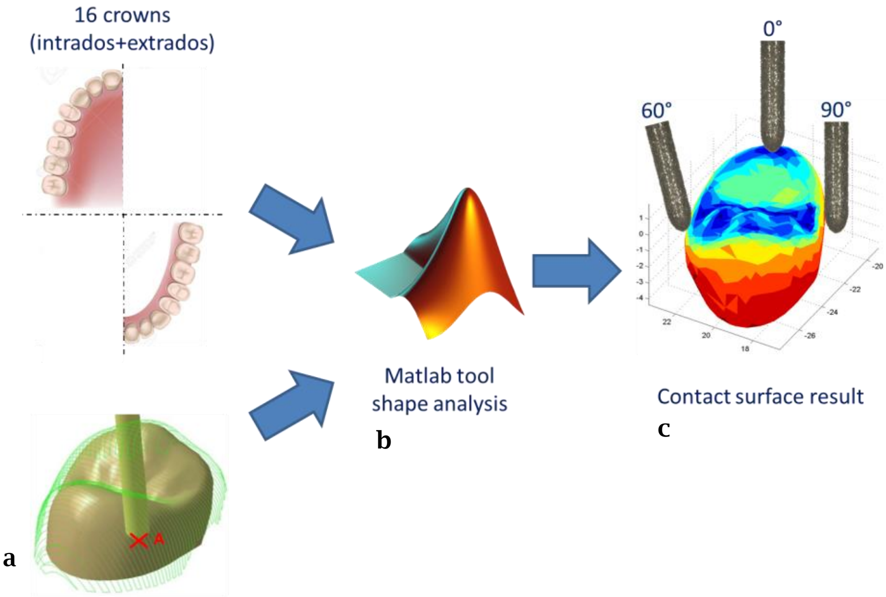

Fig. 1: Topological decomposition synopsis. (a) 16 crowns shapes milled. (b) Matlab tool shape analysis. (c) Contact surface results.

Milling experiments

Specific milling experiments are performed according to 3 more-representative contact surfaces found in the topological analysis. Eight tool/biomaterial couples are included in the experiments: 2 milling tools (Cerec pointed bur and Lyra bur) and 4 significant biomaterials indicated for crown restoration (3M Lava Ultimate, Vita Mark II, Vita Enamic, Dentsply Celtra Duo). The 8 couples are tested at 4 different feed rates (1000, 2000, 3000, and 4800 mm/min). A 4-axis dental milling center (Lyra prototype; GACD SASU) is used to perform the tests. The fourth rotary axis is used to manage the inclination angle between the tool axis and the crown surface. This milling center is fitted with a spindle speed of 60 000 RPM. The machine is warmed up before milling. Coolant is sprayed on the tool-material contact zone.

Roughness measurements capitalization

For each 96 configurations the roughness is evaluated. Two- and 3-dimensional (2D and 3D) roughnesses are measured with a focal variation device (InfiniteFocus; Alicona Imaging GmbH). The 2D roughness profiles are recorded perpendicularly to the feed rate direction. Three profiles (approximately 1 mm in length) per specimen are recorded in the middle of the milled surface. The 2D roughness parameters determined are Ra (average roughness of profile), Rt (maximum peak to valley height of roughness profile), and Rz (mean peak to valley height of roughness profile). Three-dimensional roughness criteria are recorded on a 0.8×1 mm2 planar surface. Two surfaces, in the middle of the milled areas, per specimen are recorded. In line with the NF EN 623-4 standard [1], aberrant points are excluded from the area. The 3D roughness parameters determined are Sa (average height of selected area), Sz (maximum valley depth of selected area), and Sq (root-mean-square height of selected area). Then, the mean and the standard deviation (SD) of each roughness parameters are calculated and saved in a data basis associated to the tool implemented in Matlab. Thus, prediction maps, implemented with a PLY file format, according to the tool-biomaterial couple, and the contact between the tool and the prosthesis shape, can be generated to predict residual roughness based on experimental results.

Performance indicators

Independent roughness parameters and their results are not sufficient for evaluating final SI of prosthesis. To give an overall and reliable view and to assess SI by comparison to the clinically desired SI, 2 performance indicators are introduced. The first is a weighted relative mean performance indicator named MSI. MSI performance indicator, based on the calculation of the average, is from a mathematical point of view, a roughness position indicator. The second is a weighted relative standard deviation performance indicator named SISD. SISD performance indicator, based on the calculation of the standard deviation, is from a mathematical point of view, a roughness range indicator. The 2 performance indicators do not provide the same type of information about shape residual roughness. They are complementary and cannot substitute each other. The performance indicators are locally computed among the shape according to (1) the gap between the milling SI experiments results and the clinically desired SI, (2) the inclination angle between the tool axis and the surface, and (3) the tool-biomaterial couple (including the feed rate). The MSI and SISD are used to generate SI performance maps in PLY file format according to the prosthesis shape.

Results and Discussion:

The 16 crowns (intrados and extrados) topological decomposition results reveal that inclination angles of 0°, 60° and 90° between the tool axis and the crown surface are the 3 more-representative orientation of the contact surfaces. The 90° inclination angle is the most used to mill a crown (19.2%) and is located on peripheral areas. On these areas main clinical functions concern the non-dental plaque growth. Located around the cusps, 60° is the second most used inclination angle (10%). The 0° inclination angle is clinically significant because of the occlusal contact and wears which occur on these areas.

Measurements show that 2D and 3D roughness seem not to be dependent of feed rate. The process signature generated by the tool is anisotropic for 90° and 60° inclination angle and isotropic for the 0° inclination angle. The experimentations results show that the roughest surfaces are obtained with a 90° inclination angle, and the smoothest surfaces with a 0° inclination angle. For the same biomaterial, a relationship can be established between Ra or Sa roughness parameters and the inclination angle. Indeed, Ra and Sa parameters increase when the inclination angle changes from 0° to 60° then from 60° to 90°. With a 90° inclination angle, Vita Mark II and Dentsply Celtra Duo (hard biomaterials) the roughness is lower. At the contrary, on 3M Lava Ultimate and Vita Enamic (soft biomaterials) the roughness is higher. With a 0° inclination angle the reverse phenomenon occurs. The hardest biomaterials are milled with a highest roughness compared to the softest. Since the 60° inclination is intermediate, there is no clear trend.

A much smaller amplitude of the standard deviations during the 0° inclination angle machining, compared to that of the standard deviations of the other 2 orientations (60° and 90°) is observed. In the same way, the differences between the parameters Ra and Sa increase when the orientation successively passes from 0° to 60° and then to 90°. The 90° inclination angle machining generates the largest difference between the Ra and Sa parameters, while the 0° inclination angle machining has almost no difference between the two parameters, regardless of the tool. It is therefore important to use the appropriate inclination angle to obtain the desired roughness when machining dental prosthesis.

The experimental results show, for the 3 inclinations, that there is a predominant influence of the tool on the roughness measured. The roughness for the 60° and 90° inclinations are affected by the diamond grains size of the abrasive mills. While the influence of the diamond grains size on the roughness seems to be non-existent with a 0° inclination angle machining.

Performance indicators

Performance indicators are used to quantitatively assess the SI and compare it to clinically desired one. The two purposes of these performance indicators are: (1) Allow prediction of SI before CAD/CAM machining. Prediction is made possible by the capitalization of previous machining test results. This offers the possibility of simulating several machining conditions to target the optimal SI that at best meets the expected clinical functions. Figure 2 shows roughness parameters prediction overall the crown shape obtained under specifics milling parameters. (2) Allow a global evaluation of the SI obtained after machining by CAD/CAM without independent analysis of the roughness parameters. Thereby, a comparison of SI obtained under different machining conditions can be done. Figure 3 illustrated the 2 performance parameters results overall the crown shape obtained under specifics milling parameters and according to expected clinical functions.

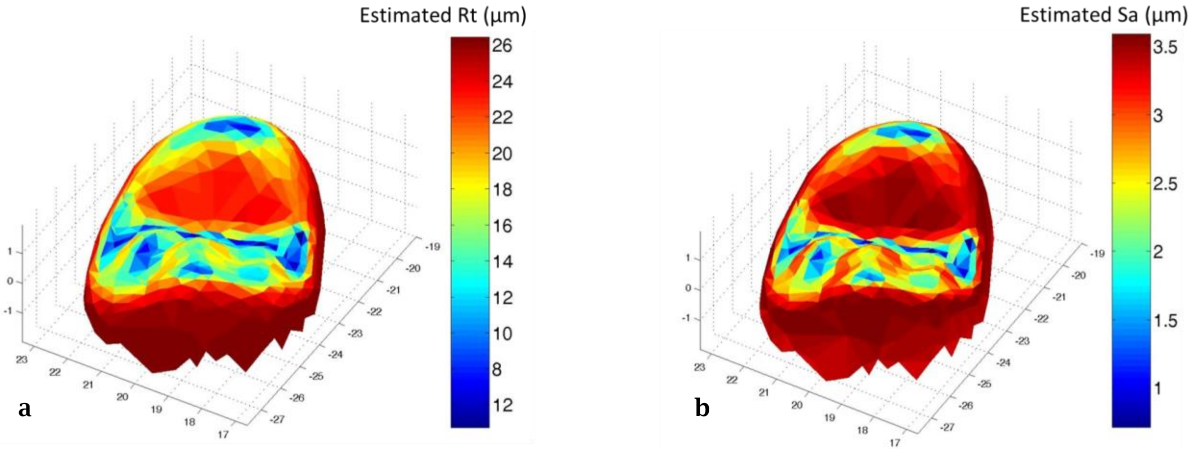

Fig. 2: Predicted roughness maps. (a) Rt 2D roughness predicted map. (b) Sa 3D roughness predicted map.

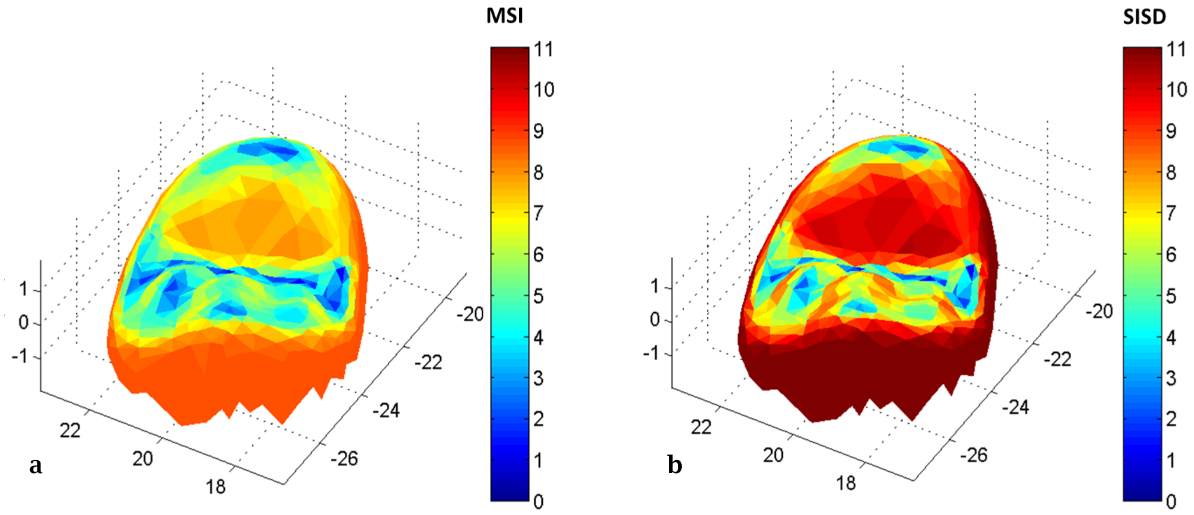

Fig. 3: Predicted SI performance indicators maps. (a) MSI predicted SI performance indicator map. (b) SISD predicted SI performance indicator map.

In our study case, the 2 performance indicators ranges are different. The MSI performance indicator ranges from 0 to 8 and the SISD performance indicator ranges from 0 to 11. However, the areas on which the MSI performance indicator is low also correspond to the areas where the SISD performance indicator is low, and conversely. The lowest performance indicators are found on the occlusal face and the highest values on the peripheral faces. On the occlusal areas, the 2 performance indicators low values show that the roughness parameters are close to those clinically expected. From a clinical point of view functions required in this area are almost respected. On the contrary, on the peripheral areas, the 2 performance indicators high values show that the roughness parameters are far from those clinically expected. The peripheral areas are far from the expected clinical functions. The use of the proposed computer-aided tool highlights the prosthetic areas needed a specific grinding post-processing by the practitioner. The comparison of SI performance indicator maps (MSI, SISD) and tool/prosthesis inclination angle maps highlights the fact that the best SI performance indicators (lowest mean and lowest standard deviation) are obtained during end ball milling with the tool tip. Indeed, on the extrados occlusal area, mostly machined with the tool tip, the roughness specifications are almost respected. Therefore, peripheral areas, to best fit the clinical expected functions, have to be machined with another milling path or a 0° inclination angle or might by manually post-processed by the practitioner.

In our study case, the 2 performance indicators shape correlation is partly due to the expected clinical functions specifications. In a general case, dealing with another SI component or with others clinical functions specifications, the MSI and SISD correlation might not be the same.

Conclusion:

A computer-aided predictive tool for crown prosthesis SI assessment after milling is proposed. This predictive tool aims at helping the prosthesis manufacturers to choose efficiently milling parameters according to the prosthesis requirements. This modular tool can be enriched by new milling experimental results and new surface integrity components. By the way, 2 SI indicators are being implemented. These indicators are being extended to the relevant SI components correlated with aesthetics, biological response and mechanical behavior requirements for fixed dental prosthesis.

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