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STABILITY ANALYSIS OF DENTAL GUIDES

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Abstract

In dental implantology surgical guides for implant placement have been used in last few years but little research has been done to preoperatively analyze stability of these guides and uniqueness of fit. Recently, few mathematical models have been developed to predict the stability of the guides prior the operation. In this study adapted mathematical model was used to investigate correlations between different mesh density representations of dental anatomical surfaces and stability scores derived from the mathematical model. Tested surfaces (guides) resulted in quite stable behavior regarding translational stability (MT = 1,27 ± 0,14) and less in the field of rotational stability (MR = 7,55 ± 4,75). Future work suggests analyzing large data set to investigate the unknown population based rules related to dental guides design process and stability.

Keywords: *dental implantology, dental guides, stability model*

1. INTRODUCTION

Computer aided design (CAD) and rapid prototyping technology (RP) in the last few years have become widely used in dental implantology. Many studies show that using preoperative planning on the computer and patient specific guides improves stability and accuracy in implant placing procedures. The guides are designed to fit in a unique position onto the patient anatomy so that preoperative plan can be easily transferred from the computer to the operation room. The main task of the guide is to provide a drilling or cutting direction for the surgeon.

Although many studies show that using custom made guides improves accuracy the procedures used are not flawless. Usage of dental drill guides still leads to deviations from the plan. The following differences might be connected to the handling of the computer tomography: The positioning of the radiographic template, image segmentation, modeling of the images and prototype production, stability of the guide on the patient anatomy or fitting of the metal sleeves [1, 2].

In this preliminary study the focus is set on stability of the dental drill guides. Recently, there have been some studies which resulted in providing a feedback through developing a mathematical model for predicting stability of surgical guides [3, 4].

Anatomical surface which is used to support the guide is analyzed during the planning procedure so that stability of the guide could be maximized. The standard form for representing anatomical 3D models is an STL file format (Standard Tesselation Language, native format for stereolitography software). The continuous surface of a 3D anatomical model is represented by discrete number of small connected surface triangles. Higher density of triangles equals to better representation of an observed surface.

Usually, anatomical models are acquired from CT/MRI images or a 3D scanner so the user doesn't know what will be the exact density of the mesh representing the surface. If there were two engineers acquiring the 3D model from the same CT/MRI image the models would not have the same number and orientation of triangles representing the surface (mesh density would be in the order of magnitude but different).

As demonstrated by research [3] the mesh density doesn't influences the stability scores derived from the mathematical model developed. If we know that representation of anatomical surface for positioning of dental guides can have up to 50k triangles, the question is wouldn't it be more efficient for analyzing the stability scores to use surfaces with fewer number of triangles when there's no influence of the mesh. That way the analysis would require fewer computer resources and also the other problem is that there is no specified threshold for the minimum mesh density so that the calculated stability scores are still valid. Although it has been proven that minor changes in mesh density don't influence the stability scores if the number of triangles would be gradually reduced to zero at some point the mathematical model has to crash.

So the idea of this preliminary study is to further investigate correlations between stability scores and mesh density and also to try finding a threshold at which the mathematical model crashes. The adapted mathematical model for analyzing stability and tests conducted are described in the following sections of this paper.

2. MATHEMATICAL MODEL

The developed mathematical model is used to verify the stable position of a surgical guide during the guide design phase. The mathematical model roots to the domain of robotic grasping and work piece fixturing. The contact points are positioned in such a way that an external force can be resisted. This requirement can be considered similar to the required stability of a surgical guide.

The original model for comparing different grasps and fixtures has been introduced by Lin et al. (2000) [5] and further developed by Van den Broeck (2015) [3]. For a given contact surface, a wrench vector w_i is created for each of the N different contact points, using its coordinates $\mathbf{p}_i$ and a unit outward normal vector $\mathbf{n}_i$:

$$w_i = \alpha_i \begin{bmatrix} n_i \\ p_i \text{ x } n_i \end{bmatrix}, \quad \text{where } \alpha_i = \sqrt{S_i} \qquad (1)$$

A weight factor α_i, based on the triangle surface s_i of each contact point eliminates influence of the STL mesh density. However, this results in a scale dependence of the analysis. To cancel out this scale effect, prior to complete analysis, the contact surface is scaled such that the mean distance of the point coordinates to the center of gravity is equal to one [6].

These can be combined in a matrix **W** for all N points:

$$\mathbf{W} = [w_1 \;\; w_2 \dots w_n] \qquad (2)$$

A spatial stiffness matrix $\mathbf{K}$ can be created using this wrench matrix:

$$\mathbf{K} = \mathbf{W}\mathbf{W}^{\mathrm{T}} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^{\mathrm{T}} & \mathbf{D} \end{bmatrix} \tag{3}$$

The 6 x 6 stiffness matrix $\mathbf{K}$ is a symmetric, positive semi-definite matrix with a block-diagonal structure, where $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{D}$ are 3 x 3 sub-matrices. These sub-matrices are used to define two new matrices:

$$\mathbf{C}_w = \mathbf{A}^{-1} \tag{4}$$

$$\mathbf{K}_v = \mathbf{D} - \mathbf{B}^{\mathrm{T}}\mathbf{A}^{-1}\mathbf{B} \tag{5}$$

The eigenvalues of these matrices have been proven to be frame-invariant [5]. The translational compliance of the contact is represented by matrix $\mathbf{C}_w$, hence the eigenvalues σ_1, σ_2 and σ_3 of the matrix $\mathbf{C}_w^{-1}$ are the principal translational stiffness parameters. These will give an indication of the translational stability of the analyzed contact surface. Matrix $\mathbf{K}_v$ represents the rotational stiffness of the contact and its eigenvalues μ_1, μ_2 and μ_3 are the principal rotational stiffness parameters.
The principal rotational stiffness parameters are scaled to allow the comparison between translational and rotational stiffness parameters. The equivalent rotational stiffness parameters are then defined, linking the rotational stiffness of the contact to a user defined target point [5]:

$$\mu_{eq,i} = \frac{\mu_i}{\rho^2 + (\omega_i \cdot v_i)^2} \tag{6}$$

Where ω_i is the eigenvector of $\mathbf{K}_v$ corresponding to eigenvalue μ_{i} and ρ is the distance of the target point to the instantaneous axis of rotation parallel to ω_i and through point q_i:

$$q_i = \frac{\omega_i \times v_i}{\|\omega_i\|^2} \tag{7}$$

And v_i is calculated as follows:

$$v_i = -\mathbf{A}^{-1}\mathbf{B}\,\omega_i \tag{8}$$

The translational stability parameter (M_{T}) and rotational stability parameter (M_{R}) have been derived from the analytic expression of the target registration error [7]:

$$M_{\mathrm{T}} = \sqrt{\frac{1}{\sigma_1} + \frac{1}{\sigma_2} + \frac{1}{\sigma_3}} \tag{9}$$

$$M_{\mathrm{R}} = \sqrt{\frac{1}{\mu_{eq,1}} + \frac{1}{\mu_{eq,2}} + \frac{1}{\mu_{eq,3}}} \tag{10}$$

The stability scores will decrease if the stiffness parameters increase and give an indication of the average quality of the contact. The scores are used to predict the translational and rotational stability of a designed guide in contact with its supporting anatomy. The closer the score is to zero, the more stable the contact will behave. The model was implemented in Matlab (v.R2012.a, The MathWorks, Inc., Natick, MA, USA).

3. METHODS

Three dental castings have been obtained from the dental clinic from three different patients. Castings have been 3D scanned using an industrial 3D scanner, Comet5 1.4MP (Carl Zeiss Optotechnik GmbH, Neubeuern, Germany). The STL files of castings were later processed in Mimics Innovation Suite software (Materialise, Leuven, Belgium) and surfaces needed for dental guides design were acquired (Figure 1).

The same surfaces that are used as a start point for design of guides are also the ones that are tested for the stability score because the guides are positioned on that surface. Some general features that describe observed surfaces are listed in the Table 1.

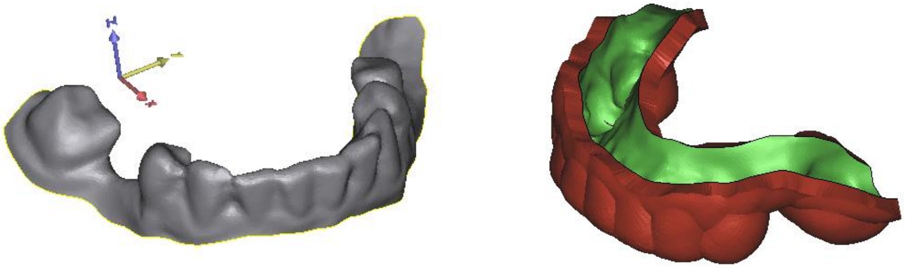
a. b.

Figure 1: a) Anatomical surface and b) Dental guide

Table 1: General surface features

	Surface A	Surface B	Surface C
Number of triangles	30992	43350	24150
Area, mm2	2518,2	3485	2096
Mesh density, NoT/mm2	12.3	12.44	11.52

As it can be observed from Table 1 every surface has different initial number of triangles representing it, so for testing and comparing between surfaces, the mesh density parameter was used to confront stability scores, and not number of triangles (NoT) representing the surface.

To find out the correlations between mesh density and stability scores the following procedure was done. The stability scores were first calculated using the original surface. After that the mesh density was reduced for 20% from the initial mesh density and the stability scores were calculated again. The two step procedure was repeated until the number of triangles representing the surface could not be more reduced. During testing it has been discovered that main disturbances of the algorithm are localized below the 20% density of the initial mesh. Accordingly, the step for mesh density reduction in that area was changed so that finer representation of the data could be achieved. The example of the data gathered during testing is presented in Table 2. Similar values have been obtained for surfaces B and C. Also, as it can be seen the computation time for running the algorithm was measured too.

Table 2: Data collected for surface A

Surface reduction, %	NoT	Mesh density, NoT/mm2	MT	MR	Computation time, s
100	30992	12.3	1.4279	4.1983	107.3067
80	24794	9.85	1.4360	4.2130	90.6916
60	18595	7.38	1.4311	4.2113	65.0448
40	12396	4.92	1.4329	4.2197	44.5713
20	6198	2.46	1.4298	4.2016	22.3367
10	3099	1.2	1.4507	4.2886	12.2291
5	1550	0.6	1.4812	4.4862	6.7815
2.5	775	0.3	1.5521	5.1375	4.0096
1,6	498	0.197	1.5838	8.4554	2.9528

4. RESULTS

The tests indicate a difference in stability for all guide designs. The data measured is displayed in the Figure 2 and Figure 3. It is expected that different guide designs (surface A, B, C) have different stability scores. This happens because of the differences in anatomy between patients. Also, it is shown that reduction in mesh density influences more on rotational stability (Figure 3), while the translational stability parameter tends to be more rigid and disturbances caused by reduction in mesh density generate smaller deviations (Figure 2).

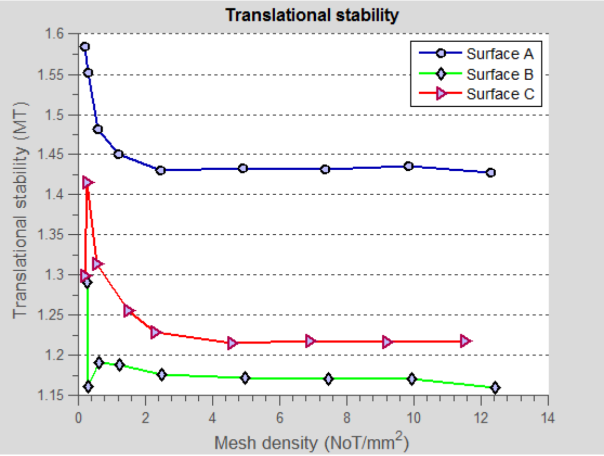

Figure 2: Translational stability

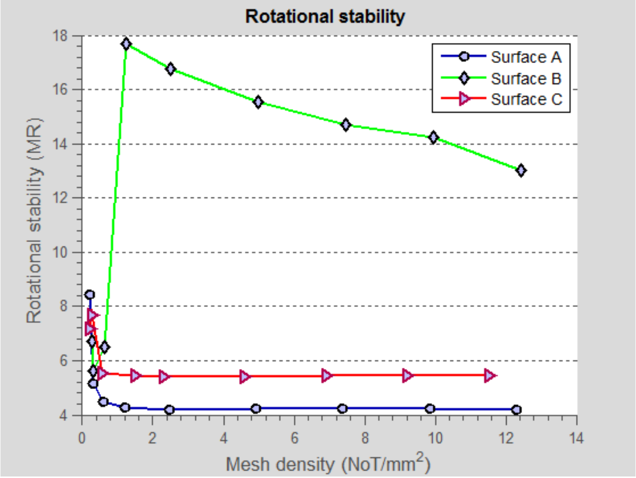

Figure 3: Rotational stability

Van den Broeck (2015) roughly determined that differences in stability score should be over 0,5 to indicate a significant difference in stability [3]. Therefore, the mesh density for dental guides can easily be reduced up to 20% of the initial mesh and the stability scores would still be valid. Very interesting behavior is seen in rotational stability test for surface B. While the mesh density is reduced the stability scores increase almost lineary. This can't be explained at this moment and should be investigated in future on large dataset. From the table 2, it can be observed that reducing mesh density speeds up the computation time. Concretely for surface A, if the mesh density would be 20% of the initial mesh the algorithm would roughly be five times faster. Similar values have also been obtained for surfaces B and C.

5. CONCLUSION

This preliminary study explains evaluating stability parameters of dental guides during design process. Van den Broeck (2015) used presented mathematical model to predict stability of surgical guides for total knee arthroplasty (TKA). There has been no application of this model in the field of dental implantology yet. Three anatomical surfaces for design of dental guides have been tested. Calculated stability scores suggest that dental guides are quite stable regarding translational stability ($MT_A = 1,43$; $MT_B = 1,17$; $MT_C = 1,21$; $MT_{AVG} = 1,27 \pm 0,14$), and less regarding rotational stability ($MR_A = 4,21$; $MR_B = 13,0$; $MR_C = 5,46$; $MR_{AVG} = 7,55 \pm 4,75$). Also mesh density has a small influence on translational stability and higher on rotational stability. If the mesh density is reduced up to 80% the stability scores would still be valid. Reducing the mesh density the stability algorithm could be up to five times faster in execution. For future work conducting a stability analysis on large dataset is a must. Analyzing large dataset could lead to general improvements in design process of dental guides, like defining optimal surfaces for guides positioning and detecting unknown population based rules.

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