Performance evaluation of dental implants: An experimental and numerical simulation study

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Abstract
Dental implants are widely used in replacing missing teeth. However, some problems may occur such as screw loosening or screw fracture which lead to implant failure. In this regard, it is of utmost importance to analyse some of the factors that affect the primary stability and consequently the osseointegration of dental systems. In the present study, particular attention is given to the bone density and the bone-implant contact in order to evaluate the implant performance.

Given the difficulty in working with bone in vivo, in the present study two implant systems were inserted in polymeric samples, of different densities, known as Sawbones, which simulate the structure of trabecular bone. The implant systems chosen were external hexagon and Morse taper. The performance of the implants was evaluated through experimental fatigue tests that simulate the chewing or mastication cycles. The qualitative analysis of the damage in the cellular structure of the samples was performed using scanning electron microscopy (SEM).

The finite element (FE) method was used to model the penetration of the implants and enable the determination of the stress at the implant and deformations at the Sawbones-implant vicinity. Prior to penetration simulations, a well-known analytical model of indentation was compared with indentation simulations, in order to validate the numerical model. The major difference between numerical and analytical model results, in the case of the displacements, was found to be around 9%.

The failure of the Sawbones occurred with the propagation of the collapsed cells according to SEM observations. The fatigue results showed that the Morse taper implant exhibited lower displacements than the external hexagon. Higher density Sawbones also exhibits lower deformations, while keeping the other parameters constant. It means that Morse taper and high dense materials show a better fatigue performance than the other systems and materials.

The FE results for penetration showed that a threaded geometry implant when compared to smooth geometry provided a reduction of the stresses in the implant and reduces the deformations in the Sawbones.

The results of the penetration simulations follow the same trend as the indentation simulations and analytical model. Simulation results show that the displacements are reduced with the increase of the density of the polymer foam. This is in agreement with the fatigue results. Comparing bones with foams, it could be concluded that, the increase of the bone density will induce a higher stability of the implants.

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1. Introduction

In recent times dental implants have been considered a good solution for lack of dentition, being considered the best alternative after natural teeth. However, in spite of the latest advances in dentistry, implants are still likely to fail. Complications at the bone-implant interface, such as bone loss, occurrence of micromovements and stress concentration at the bone-implant interface, are very common phenomena that affect the stability of the implant [1]. Two types of stability are defined, primary and secondary, being the latter related to bone generation and remodelling. Although bone presents an adaptive behaviour due to loading stimulus that consists in sequences of bone formation...
and resorption, bone remodelling will not be considered in the present study. Therefore it is assumed that the density remains constant.

Primary stability is critical in the success of implants and is considered to be a determining factor for osseointegration. Primary stability is related to an absence or to a high resistance to micro-movements. In fact, the dental micromovements must be less than 150 μm in order to prevent implant failure [2]. Factors that influence the primary stability are surface properties, surgical technique, implant design or bone quality [3]. Bone quality is evaluated by density and quantity of trabecular and cortical bone [3]. When an implant is placed, the primary stability will depend, essentially, on the quantity of cortical and trabecular bone available for the fixation of the implant [2].

Throughout time, the implants will be subject to different types of loadings, resulting from the chewing and mastication process. This is why it is of the highest importance to submit dental implants to cyclic loading. Fatigue tests reproduce experimentally the mastication process and allow evaluation of the long term stability of an implant system in different substrates [4–6].

From a biomechanical perspective, a well-succeeded osseointegration of dental implant depends on how the stresses and deformations are transmitted to the bone and its surrounding tissues. The stress and strain distributions in bone and implant are affected by many variables, such as the type of loading, the length and diameter of the implant, its geometry, the bone-implant surface, and the quality and quantity of surrounding bone [7,8]. The FE method allows analysing the influence of the variables, and for that reason it has become the most used simulation tool to analyse the failure of the dental system.

Given the difficulties to work with trabecular bone, synthetic polyurethane foams are widely used as alternative materials to this type of bone in several biomechanical tests, due to the fact that these materials present a similar cellular structure and equivalent mechanical characteristics [9]. Sawbones are polymeric materials which are used as a standard material for performing mechanical tests according to ASTM F-1839-08 [10].

Despite the fact that artificial foams have limitations and do not fully represent the real human jawbone, as their structural and mechanical properties are much more homogeneous in comparison with real bone, they are widely used in biomechanical testing, simulation and on the evaluation of implant stability [3,11–13]. In the experiments by Liu et al., three Sawbones foams were selected with densities of 0.16; 0.20; 0.32 g/cm³, named respectively Sawbones 10, Sawbones 11 and Sawbones 12, to assess the relation between insertion torque and bone-implant contact area [13].

The density and the porosity of the mandibular bone vary with the location (anterior, middle and distal) in the mandible [14]. According to the Misch classification for bone density, bone types D1, D2 and D3 can be found, being D1 the highest dense and D3 the lowest dense bone [14]. In fact, D3 is formed by an open trabecular structure and a thin cortical part, while the D1 bone corresponds to a higher dense trabecular and cortical parts.

The aim of the present work was to study the effect of the trabecular bone structure, in particular bone density, and bone-dental implant contact on the dental implant performance. Fatigue tests were performed according to the ISO 14801 standard with two implant systems: hexagonal external and cone Morse. Each implant was inserted in polymeric samples from Sawbones, with different densities, simulating different bone types, to assess the stability of the implants and the deformations in the Sawbones-implant vicinity. This study was complemented with analytical and numerical analyses. CAD geometries, similar to the test specimens, were generated, through which it was possible to generate FE meshes and subsequently determine the deformation fields of the Sawbones and the stress at the Sawbones-implant vicinity.

2. Materials and methods

2.1. Preparation of test specimens

The insertion material used consists on rigid polyurethane foams, known as Sawbones acquired to the company Sawbones (Vashon Island, Washington, USA).

The three different densities of the Sawbones used were chosen by the present authors after carrying out an image analysis evaluation of the porosity of the trabecular bone found in the different regions of the mandible. For the bone type D1, D2 and D3, the values of the porosity obtained, in the present work, were respectively, 46, 56 and 72%. According to Liu et al., the porosity of the Sawbones 12, 11 and 10 is 62.3, 66.1 and 79.2% (Table 1) [13]. In view of the values of porosity of the Sawbones and porosity of bone D1, D2 and D3, one may establish a correlation between Sawbones and bone type. In this sense, it could be assumed that the Sawbones 10 with lower density aims to simulate a D3 bone type, the Sawbones 12 represents a D1 bone type, and finally, the Sawbones 11 is associated to a D2 bone type.

Cubic samples of Sawbones were prepared with dimensions of 13 × 15 × 15 mm. In order to simulate the cortical part of the bone, an epoxy resin layer of thickness of 2 mm was glued to the polyurethane foam cubes (Fig. 1a). This is in accordance with the procedure defined by Liu et al. [13].

Although an implant system is formed by the implant, abutment, screw and crown, the present work will not feature the crown. For the experimental fatigue tests, two types of implants were tested: the external hexagon and the Morse taper with the respective abutments, shown in Fig. 2. Dental systems were obtained from DIO, Busan, Korea. The identification of the implant material was made through the chemical analysis carried out in a field emission gun scanning electron microscope (FEG–SEM) (JEOL model 7001F) with an X-ray energy-dispersive system (EDS). The results of such chemical analysis showed that the implants are produced with commercially pure titanium grade 4.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Sawbones 10</th>
<th>Sawbones 11</th>
<th>Sawbones 12</th>
<th>Epoxy resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>0.16</td>
<td>0.2</td>
<td>0.32</td>
<td>1.64</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>79.2</td>
<td>66.1</td>
<td>62.3</td>
<td>–</td>
</tr>
<tr>
<td>Cell size (mm)</td>
<td>0.5–2</td>
<td>0.5–1.5</td>
<td>0.5–1</td>
<td>–</td>
</tr>
<tr>
<td>Compressive</td>
<td>2.3</td>
<td>3.9</td>
<td>5.4</td>
<td>157</td>
</tr>
<tr>
<td>strength (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young’s modulus (MPa)</td>
<td>23</td>
<td>47.5</td>
<td>137</td>
<td>16.7</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Fig. 1. Preparation of the samples (a) Sawbone cube and epoxy resin layer; (b) a hole with a diameter of 4 mm (for external hexagon) or 4.5 mm (for the Morse taper) was drilled according to the surgical protocol.
A hole (Fig. 1b) was drilled at the Sawbones sample in order to insert the dental implants. The preparation of the test specimens was made based on the surgical protocol and the drilling sequence recommended by the implant manufacturer. Four drills with different diameters and rotation speeds were used with diameters of 2.0, 2.8, 3.3 and 4.0 mm in the case of the external hexagon, while the last drill in the case of the Morse taper was of 4.5 mm. The rotation speeds were higher (1010 r.p.m) in the case of the two smaller drills, while for the two higher diameter drills, the speed was reduced to 865 r.p.m. The implant insertion was done with a dental torque wrench, where the reading of the applied torque was possible, as shown in Fig. 3. A hemispherical load member was placed over the dental system, to simulate the crown.

2.2. Fatigue tests

Fatigue tests were conducted in a servo-hydraulic testing device (Instron 8502) with a load cell of 10.0 kN, with a frequency of 3.0 Hz and R = 0.1. All the fatigue tests had durations of 120,000 cycles. An oblique load was applied in an adaptation of ISO 14801, so that the dental implant axis makes a 30° angle with the loading direction. The average force applied to the test specimens corresponds to the lower value (75.0 N) and the upper limit of the average chewing or mastication force of an individual, which may be considered to be 150.0 N [6,15,16]. The results were handled through plots of displacement versus number of cycle.

2.3. Failure analysis

After the fatigue tests, the Sawbones samples were cut in two parts, covered with a conductive layer and observed in the field emission gun scanning electron microscope (FEG-SEM) (model 7001F, JEOL), with an accelerating voltage of 10 kV, using secondary electrons. SEM images allow the identification of the flaw sites.

2.4. Analytical model for indentation

Several engineering problems involve some sort of mechanical contact. The model chosen to validate the numerical simulations was a classic model of indentation for elastic materials, because analytical models for penetration are rare. Based on the mechanical theory of contact, the model describes the deformation occurring on a material, resulting from the pressure applied by an indenter for isotropic materials under frictionless conditions [17]. Assuming a cylindrical indenter contacting on a surface, we have at a radial distance, r, smaller than the contact radius, a (r ≤ a), the axial (z direction) stress and displacement components:

\[
\sigma_z = -\frac{1}{2}\left(1 - \frac{r^2}{a^2}\right)^{-\frac{1}{2}}
\]

\[
u_z = \frac{1 - v^2}{E} p_m \frac{r}{a}
\]

where \(p_m\) is the contact pressure, \(E\) the Young's modulus, \(v\) is the Poisson coefficient. Also for a cylindrical indenter, the radial stress at the indented surface is given by:

\[
\sigma_r = -\frac{(1 - 2v)}{2} \frac{a^2}{r^2} \left\{1 - \left(1 - \frac{r^2}{a^2}\right)^{-\frac{1}{2}}\right\} - \frac{1}{2} \left(1 - \frac{r^2}{a^2}\right)^{-\frac{3}{2}}
\]

while the radial displacement at the indented surface is:

\[
u_r = -\frac{(1 - 2v)(1 + v)}{3E} \frac{a^2}{r^2} p_m \left\{1 - \left(1 - \frac{r^2}{a^2}\right)^{\frac{3}{2}}\right\}
\]

Eqs. (1) to (4) allow the calculations of the stress and displacements in the both z and r directions, for a cylindrical indenter.

2.5. Numerical analysis with finite element method (FEM): indentation and penetration

Finite element simulations enable the determination of the stress fields and deformations at the Sawbones-implant vicinity. The properties of the different foams, epoxy resin and titanium implant are shown in Tables 1 and 2. Initially, the numerical model was validated by comparison with the results issued by the indentation analytical model. To simplify, the indenter was considered as having a smooth profile (Fig. 4). In the case of the finite element model of penetration,
two distinct geometries for the implants were considered, one smooth and other threaded. The SolidWorks 2015 program was used to generate CAD files that were subsequently exported to the ANSYS Workbench 14.5 commercial code. The CAD geometries and the meshes used in the FE simulations are indicated in Fig. 4.

Penetration simulations were performed with two geometries of the implant, smooth and threaded, while on the indentation model only the smooth geometry was studied. To generate the mesh of smooth geometry implant the element SOLID186 was used while for the threaded geometry implant the element SOLID187 was applied.

The convergence test of the FE models was performed to verify the mesh quality, and the convergence criterion was set to be less than 7% changes in the highest von Mises stress. The mesh convergence error stayed below that threshold, both for smooth geometry (6.97%), as well as in the case of comparison with the threaded implant (6.83%). For the penetration simulations, the number of elements in the mesh was 37,731 for the smooth implant and 187,823 for the threaded geometry. The mesh used in the indentation simulation had 19,572 elements. Element sizes were 0.48 mm (smooth implant penetration), 0.58 mm (threaded implant penetration) and 0.6 mm (smooth implant indentation).

The epoxy layer, implant and bone substitute were considered homogeneous, isotropic and linear elastic materials [16,18].

Initially the numerical simulations of penetration were made with the type of contact designated as bonded of the ANSYS code, in order to reproduce a good osseointegration of the implant. However, the type of contact between Sawbone and epoxy with the implant was changed to no separation, which allows for, limited but frictionless, sliding between surfaces. This second type of contact was found to simulate better the penetration of the implant system on the surface of the foam due to the complexity involving the foam microarchitecture.

For the boundary conditions, the lateral faces of the epoxy and all the Sawbone faces were constrained in the three directions, $x$, $y$ and $z$.

Penetration simulations were undertaken for the three types of Sawbones and for two applied loads, 70.0 and 150.0 N, while the loads, for the indentation case, were 60.6 N and 129.9 N.

The von Mises criterion (invariant) was used to compute the stresses.

3. Results

3.1. Fatigue tests

The curves obtained in the fatigue tests for the implant systems external hexagonal and Morse taper inserted in Sawbones 10, 11 and 12 are exhibited in Figs. 5–7. The explanation of the shape of the displacement-number of cycles curves take into account that in cellular solids, the mechanisms associated with the stress-strain compressive curves are the same as the ones of the distinct zones of the displacement – number of cycles curves [20,21].

The curves revealed that in a first stage and for a low number of cycles the materials response was essentially linear elastic. There was a rapid accumulation of deformation caused by the bending and stretching of the cell walls, until the yield point, which was associated with the collapse of the first cell. Then, after overcoming this peak, there was a slight decrease of deformation as a result of the softening of the material. At the end of this phase, starts a level where the deformation in the material increases slightly with the

Table 2
Properties of titanium grade 4 [19].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>4.55</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>120</td>
</tr>
<tr>
<td>Tensile yield strength (MPa)</td>
<td>570</td>
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<tr>
<td>Tensile strength (MPa)</td>
<td>690</td>
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<tr>
<td>Compressive strength (MPa)</td>
<td>400</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Fig. 4. CAD geometries of (a) smooth geometry and (b) threaded geometry of implant used in the penetration simulations; (c) mesh of smooth implant; (d) mesh of threaded implant; (e) mesh of assembled parts used in the indentation simulations.
number of cycles. It was during this phase that occurred the plastic collapse phenomenon [22].

The applied load has an effect in the experimental fatigue results. Curves obtained with the external hexagonal system and Sawbones 10, which is the foam with the worst mechanical behaviour, with \( F = 75.0 \) N, show no increase in the deformation in the collapse zone, while for \( F = 150.0 \) N there is an increase of deformation with the number of cycles. However in the fatigue curves acquired with Morse taper and Sawbones 10, with the loads \( F = 75.0 \) N and \( F = 150.0 \) N, the deformation does not change much with the number of cycles, being the progress of the two curves substantially the same. Apart from the shape of the curves, one may note that at the end of fatigue tests, \( N = 120,000 \) cycles, keeping the same dental system and Sawbones, an increase in load implies higher deformations.

With the exception of fatigue tests performed with the Sawbones 10 that exhibits a different behaviour from the others, one may state that at the end of the test, displacements are lower with Morse taper than with external hexagonal, under the same load conditions and the same Sawbones. Results obtained with the same dental system and applied load showed that the displacements for \( N = 120,000 \) cycles are lower for the highest density Sawbones. It means that a better fatigue behaviour is obtained with the Morse taper system and the highest density foam.

### 3.2. FEM indentation simulations and analytical model

Eqs. (1) to (4) of the analytical model were used to evaluate the deformation and the stress at a radial distance \( r/a = 0.5 \), with contact radius \( a = 2 \) mm. The Sawbones entire displacement was calculated as \( u = \sqrt{u_x^2 + u_y^2} \), while the whole stress was \( \sigma = \sqrt{\sigma_x^2 + \sigma_y^2} \). The numerical simulations of indentation are shown in Fig. 8, where the deformation and the stress fields are plotted.
Table 3 indicates both numerical and analytical results for the three types of Sawbones and two values of the applied load. The analytical equations validated the finite element model, having manifested a 9.1% relative error for displacements and 5.5% for stresses. The stresses calculated by the analytical equations are not sensitive to the bulk properties of the Sawbones, as only the Poisson ratio is included and it has the same value of 0.3, for the three Sawbones.

The results of numerical simulations and analytical calculations showed that the deformation values decrease for the Sawbones with higher density and higher stresses.

3.3. FEM penetration simulations

Examples of the numerical results of the penetration simulations with a smooth indenter with the same applied load are given in Figs. 9 and 10, where the deformation at the Sawbones (Fig. 9) and the stress at the implant vicinity - Sawbones (Fig. 10) are shown. One may notice that the maximum stress is achieved at the contact zone of the implant and the epoxy resin.

From Figs. 9 and 10, it can be noted that the deformations of the three different Sawbones are different among each other and, as the density of the foam increases, the displacements and the stresses were found to decrease. From the point of view of stress analysis, it can be said that the most favourable situation occurs with the denser Sawbones, because the stress values were minimized. Regarding the deformations on Sawbones, it was in the less dense than the highest values occurred. Given the nature of the applied compressive force at the implant, the maximum deformation occurred at the contact vicinity between the implant base and the Sawbones, a situation which was found for all values of density and intensity load tested. As the load increases from 70.0 N to 150.0 N, the displacements in the Sawbones were also higher.

The results of the threaded geometry of the implant were very similar to those previously found for the smooth geometry (Table 4 and Fig. 11). For example, an increase of the Sawbones density is reflected in a reduction of deformation and stress.

The threaded geometry provided a reduction of the stresses in the implant and reduces the deformations in the Sawbones in comparison with the smooth geometry. In fact, a threaded implant induces a larger contact area of the vicinity between the implant and the Sawbones when compared to a smooth profile, which promotes a reduction in the amount of stress, while maintaining the same loading.

3.4. SEM observations and failure analysis

Through the SEM observations of the longitudinal sections of the Sawbones after the fatigue tests, it was possible to identify the regions of the collapsed cells (Fig. 12). It was observed that
the number of collapsed cells within the affected area were larger for the less dense structure. The damage of the samples is higher for the lowest dense material which has the lowest yield stress, in a way that the collapse starts at lower loads than in case of the dense foam. One may observe that the collapse of cells is accompanied with the fracture of the cell walls, which resembles real bone where there is the formation of microcracks in individual trabeculae at early stages of fatigue testing [20].

4. Discussion

Implant stability is difficult to evaluate as it depends on several factors such as mechanical design, geometry and quality of bone, applied load and contact area between implant and bone.

Cyclic behaviour of dental implant systems inserted into polymeric foams is an effective way to reproduce the mastication process in the laboratory. During mastication, the load may vary in accordance to higher/lower efforts made by teeth. The effect of the variation of the applied load was detected in the present fatigue tests, which revealed that an increase in the applied load lead to larger displacements at the Sawbones, for the same number of cycles, support foam and dental system.

Differences were detected on the fatigue behaviour obtained for the two tested implant systems. Tests made with the same load

<table>
<thead>
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<th>Smooth</th>
<th>Threaded</th>
</tr>
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<tr>
<td>$u$ (mm)</td>
<td>$r$ (MPa)</td>
</tr>
<tr>
<td>Sawbones 10</td>
<td>0.567</td>
</tr>
<tr>
<td>Sawbones 11</td>
<td>0.292</td>
</tr>
<tr>
<td>Sawbones 12</td>
<td>0.106</td>
</tr>
</tbody>
</table>

Fig. 10. Numerical simulations results of penetration: stress at the implant interface-Sawbones; (a) Sawbones 10; (b) Sawbones 11; (c) Sawbones 12, for $F = 70.0\, N$ and a smooth geometry of the implant.

Fig. 11. Numerical simulations results of penetration (a) displacement/deformation at the Sawbones; (b) stress at the implant interface - Sawbones, for Sawbones 10 and $F = 70.0\, N$ and a threaded geometry of the implant.

Fig. 12. SEM images (a) Sawbones 10; (b) Sawbones 12, after fatigue tests with external hexagon systems. A contour line for the affected area is represented.
implant-epoxy resin, which is accordance with other simulations and Sawbones, but different implant systems, showed that at the end of same number of cycles, the displacements at the foams are lower for the Morse taper system. Also, this type of implant was less sensitive to load variation when it was tested with the same cell structure. Both external hexagonal and Morse taper systems inserted into different density Sawbones provided lower displacements with the highest dense foam. This means that the structure of the Sawbones was able to accommodate the movements of the implant. From the point of view of the bone structure, this means that a D1 bone type, being denser and mechanically stronger than the other types of bones, will induce lower displacements.

At the end of the fatigue tests, SEM observations revealed that the highest density material was less damaged than the others with lower density, having also a lower number of collapsed cells. The present results confirm the good performance of the Morse taper system, when compared with the behaviour of the external hexagonal implant. The success is due to its “locking mechanism”, because the shape of the system is designed to reduce vibrations and micromovements [23]. In fact, the introduction of microthreads in the implant neck region helps to minimize the amount of stresses along that zone, resulting in a decrease of bone loss after the placement of the implant [2]. Also the Morse taper implant has a higher diameter and length in comparison with external hexagon. Increasing the implant diameter promotes a reduction in the normal and shear stresses along the bone-implant vicinity, leading to a better distribution of loads in the tissue [16,18].

An analysis of the stresses on the implant and bone is important to carry out, since both structures should not be stressed beyond a certain value [24,25]. The stress analysis was performed using the finite element method.

A validation of the FE simulations was conducted using an analytical model of indentation. Differences in the numerical and analytical results, in the case of the displacements, were around 9%, which enable to proceed to other FE calculations as the penetration simulations. Indentation results also show that Sawbones of high density give rise to lower values of displacements.

Larger stress concentrations were found at the contact zone of implant-epoxy resin, which is accordance with other simulations where the higher stress values occur at the contact area of implant-cortical bone [8]. Fig. 13 features the values of displacement of foams calculated with numerical simulations of indentation and penetration and the displacements obtained through the analytical model of indentation, for the three Sawbones with different densities. Maximum stress at the implant vicinity -Sawbones obtained with analytical indentation model, numerical simulations of indentation and numerical simulations of penetration, for the three Sawbones are summarized in Fig. 14.

As mentioned previously, results of indentation both numerical and analytical match well. The magnitude of displacement (Fig. 13) and maximum stress (Fig. 14) is not the same, when comparing the numerical values of the penetration with indentation simulations. However, one may observe that the trends are the same in both simulations. Despite the analytical values of the model of indentation being far from the displacement and stress obtained under penetration simulations, the model allow to understand the implant behaviour when inserted into a polymeric sample. Independently of the model or simulations, the displacement always decreases as the density increases, while the stress is almost constant. One can also observe that implants inserted in Sawbones 12 are less sensitive to load changes (Fig. 13).

Results obtained with penetration simulations demonstrated the effect of the implant design, cylindrical versus threaded, on stress distribution and Sawbones displacement. A reduction in stress and displacements for the threaded geometry is in accordance with the model of Winter et al. [7].

From the numerical simulations and fatigue experimental tests one may state that as the Sawbones density increases the displacements at the foams are reduced. According to the literature, excessive micromovements between the implant and surrounding bone should be avoided as they can interfere with the process of osseointegration [2,7]. Sawbones are a test material used to simulate the several characteristics of trabecular bone, being assumed that the Sawbones 10, 11 and 12, are representatives of D3, D2 and D1 bone types. In accordance Sawbones 12, the highest density material reproduces D1 bone, which provides small displacements, with lower micromovements of the implant relative to the bone microstructure, favouring the long-term osseointegration.

Fig. 13. Final displacements of the foams obtained with analytical indentation model, numerical simulations of indentation and numerical simulations of penetration, for the three Sawbones (Sawbones 12 is the one with the highest density).
5. Conclusions

The effects of the trabecular bone density, bone-implant contact and design on the dental implant performance were evaluated. These aspects are of clinical importance as they affect, for example, the strain in the trabecular bone, which is not well understood.

The analysis of the experimental fatigue behaviour of implants, external hexagon and Morse taper, inserted on different substrates was complemented with an analytical and finite element study, in order to calculate the stress and strain distributions in the implant and in the bone. As trabecular bone is difficult to obtain, Sawbones foams were used as substrate materials.

SEM observations of the samples at the end of fatigue tests indicate that the failure of the Sawbones happened with the propagation of the collapsed cells, the collapse regions being larger in the case of the lowest dense foam.

The results of the fatigue tests showed that the performance of the Morse taper implant (higher diameter and length) was better than the external hexagonal implant when both were tested in samples of various densities, as it leads to smaller displacements. This superior fatigue behaviour presented by Morse taper system explains its increased choice in clinical applications. The highest density Sawbones was the one that showed the lowest deformation, exhibiting a better fatigue performance.

An analytical model validated the numerical simulations for indentation using the FE method. The displacement and stress results obtained with the penetration FE model exhibit the same trend as the analytical results and FE indentation simulations of penetration, for the three Sawbones (Sawbones 12 is the one with the highest density).

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