Experimental & FEM Analysis of Orthodontic Mini-Implant Design on Primary Stability

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Abstract: The main objective of this research is to establish a connection between orthodontic mini-implant design, pull-out force and primary stability by comparing two commercial mini-implants or temporary anchorage devices, Tomas®-pin and Perfect Anchor. Mini-implant geometric analysis and quantification of bone characteristics are performed, whereupon experimental in vitro pull-out test is conducted. With the use of the CATIA (Computer Aided Three-dimensional Interactive Application) CAD (Computer Aided Design)/CAM (Computer Aided Manufacturing)/CAE (Computer Aided Engineering) system, 3D (Three-dimensional) geometric models of mini-implants and bone segments are created. Afterwards, those same models are imported into Abaqus software, where finite element models are generated with a special focus on material properties, boundary conditions and interactions. FEM (Finite Element Method) analysis is used to simulate the pull-out test. Then, the results of the structural analysis are compared with the experimental results. The FEM analysis results contain information about maximum stresses on implant–bone system caused due to the pull-out force. It is determined that the core diameter of a screw thread and conicity are the main factors of the mini-implant design that have a direct impact on primary stability. Additionally, stresses generated on the Tomas®-pin model are lower than stresses on Perfect Anchor, even though Tomas®-pin endures greater pull-out forces, the implant system with implemented Tomas®-pin still represents a more stressed system due to the uniform distribution of stresses with bigger values.

Keywords: mini-implants; primary stability; pull-out test; Abaqus; FEM analysis

1. Introduction

The main objective of successful orthodontic treatment is achieving stable anchorage [1–3]. In the last decade, great effort was put into achieving skeletal or so-called absolute anchorage, with the use of small titanium screws. Different experimental research led to the conclusion that screws, plates and similar mini-constructions enable absolute anchorage, which, compared with classic dental implants, offers insignificant anatomical limitations, easy application and lower prices. Still, one of their biggest advantages is the possibility of usage immediately after implant application [4–6]. Primary stability is the basic precondition of absolute anchorage establishment in orthodontic treatment, and it is achieved with a mechanical bond between the mini-implant and the bone [7].

The function of an orthodontic mini-implant is to provide a stable anchorage. They are temporary; they usually remain in place for some months of treatment, and then they are removed. From the orthodontic treatment point of view, the use of classical osseointegrating dental implants has many more negative aspects. One of the main disadvantages is the long period of osseointegration of the implant before it can be loaded with force (even from 4 to...
6 months). Additionally, it would require a rather painful and invasive surgical protocol, which is expensive and uncomfortable for the patient, and in the end, their use with patients under 16 years of age was excluded. During the last decade, a great effort was made in order to achieve a skeletal or absolute anchorage, using various types of small titanium screws and plates. The conclusions of many studies conducted are that screws, plates and similar mini-constructions can provide an absolute anchorage, compared with conventional dental implants, they are much less invasive, have an anatomical limitation of implantation, are simple and easy to put in and remove, less expensive than conventional implants, can be used with children and, in general, significantly improve orthodontic treatment with minimal disturbances to the patient. One of their most important advantages is that they can be loaded with force immediately after placement. Nevertheless, despite all the possibilities that orthodontic mini-implants offer, there are certain problems that occur. It is primarily about loosening and prematurely removing the screw or miniplate. Unlike dental implants, which achieve stability through osseointegration, the stability of mini-implants is achieved through mechanical retention. Compared to dental implants, the degree of stability of mini-implants is relatively low. Since the use of a temporary skeletal anchorage does not require osseointegration, primary stability is of great significance for clinical success.

The effects of mini-implant design and load distribution on the implant–bone system are subjects of very advanced scientific researches these days. Many factors, such as load type, material properties and nature of established bond, have an impact on primary stability and load distribution on the implant–bone system [8–10].

The purpose of the pull-out test is to present mechanical characteristics of primary stability for the better understanding of the behaviour of a mini-implant inserted into the bone along with the effects of geometric parameters of a mini-implant (main thread diameter, smallest core thread diameter, thread length, thread shape factor, etc.) on primary stability [11–15].

FEM analysis has become an increasingly used tool in the field of medicine, where the behaviour of any structure can be predicted with geometry modelling, complex material properties, boundary conditions and loads [16]. Analysis results give insight about stress distribution and biomechanical changes in the implant–bone system. This method gives favourable degree of reliability and accuracy “without the risks and expenses of implantation” [17].

2. Materials and Methods

An experimental in vitro study was conducted on two types of mini-implants or temporary anchorage devices (TAD) by manufacturers, Tomas®-pin and Perfect Anchor, as shown in Figure 1. Forty mini-implants were tested, where:

- twenty implants were from Tomas®-pin (SD06, Dentaurum GmbH & Co. KG, Ispringen, Germany) with a thread core diameter of 1.6 mm and thread length of 6 mm;
- twenty implants were from Perfect Anchor (OA1608, HUBIT Co. Ltd., Anyang-si, South Korea) with a thread core diameter of 1.6 mm and thread length of 8 mm.

The common property of the tested implants is their material. The implants are made from Grade 5/Ti6Al4V Titanium. Both implant types are self-drilling, which means that no preparation is needed for insertion process [18,19].
Figure 1. Mini-implants (right-to-left: Perfect Anchor and Tomas®-pin, respectively).

Swine ribs were used as experimental specimens. The number of ribs corresponded to the number of mini-implants. Swine rib preparation considered complete removal of soft tissue. Ribs were not cut, or treated with any substances, in order of preserving the bone’s structural properties.

2.1. Mini-Implant Design

The geometric analysis of orthodontic mini-implants considers measurements of thread parameters, such as length, pitch, bearing depth, diameter at multiple points, etc., as shown on Figure 2. Mini-implants are scanned with the two-coordinate measuring microscope Zeiss-ZKM 01-250 C (ZKM 01-250 C, Carl Zeiss Industrielle Messtechnik GmbH, Oberkochen, Germany), which is used for different measuring operations that involve lengths and angles. The measuring process is performed with magnification of 50×, so that all important geometric parameters would be taken into account. Values of geometric parameters are shown in Table 1.

![Diagram of geometric analysis](image1.png)

(a)

![Diagram of geometric analysis](image2.png)

(b)

Figure 2. Detailed geometry. (a): Tomas®-pin, (b): Perfect Anchor.

| Implant Type/Geometric Parameter | Perfect Anchor | Tomas®-pin |
|----------------------------------|---------------|------------|
| Core diameter, d [mm]            | 1.6           | 1.6        |
| Thread length, h [mm]            | 7.7           | 6          |
| Minimum core diameter, d1min [mm]| 0.8           | 1.04       |
| Maximum core diameter, d1max [mm]| 1             | 1.2        |
| Pitch, p [mm]                    | 0.8           | 0.9        |
| Bearing depth, D [mm]            | 0.3           | 0.26       |
| Thread coil climb angle, β [°]   | 16            | 16         |
| Core cone half-angle, α [°]      | 1.5           | 2          |
| Conicity of thread core, 1:k     | 1:24          | 1:17       |
| TSF, [%]                         | 37.5          | 29         |

2.2. Bone Characteristics
The acquired values are used for calculation of the thread-shape factor (TSF), which represents the ratio of the thread-bearing depth and pitch. This factor is characterized as the bearing evaluation factor for the implant–bone system, and it is particularly important for primary stability [20].

Table 1. Values of geometric parameters established with measuring.

| Implant Type/Geometric Parameter | Perfect Anchor | Tomas®-pin |
|----------------------------------|----------------|------------|
| Core diameter, d [mm]            | 1.6            | 1.6        |
| Thread length, h [mm]            | 7.7            | 6          |
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| Maximum core diameter, d_{max} [mm] | 1             | 1.2        |
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| Bearing depth, D [mm]            | 0.3            | 0.26       |
| Thread coil climb angle, β [°]   | 16             | 16         |
| Core cone half-angle, α [°]      | 1.5            | 2          |
| Conicity of thread core, 1:k     | 1:24           | 1:17       |
| TSF [%]                          | 37.5           | 29         |

2.2. Bone Characteristics

The measurement of the cortex thickness on mini-implant insertion zone is performed with Cone Bean computed tomography. The examination of samples was performed in the Faculty of Dental Medicine of University of Sarajevo, using the GALILEOS Comfort plus instrument (Sirona Dental System GmbH Fabrikstrasse 31 D-64625 Behshein, Germany, September 2013) shown on Figure 3a. Cone Beam images are simple to use; they obtain marrow and soft tissue structures and give more data than regular 2D images [21–24].

The middle of a flat rib surface is marked for implant insertion. Location positioning is enabled with a cotton wool roll and ligature wire. The cotton wool roll provides wire separation from the measuring region, where wire shining and cortex overlap is avoided. This way, measurement accuracy is preserved. With the help of the laser, the bone is positioned so that the implant insertion location is in the middle of the measuring region Figure 3b. The cortex measurement is performed with Galileos Implant Viewer software.
(V 1.9, SICAT GmbH & Co. KG, Bonn, Germany, 2014). This software enables multiple measuring features for anatomic structures (bone density, length and width, etc.). The swine rib cortex is measured in sagittal cross-section, with a 90° angle, regarding the ligature wire. The measurement is carried out on all 40 specimens, where cortex thickness in an interval of 0.6–0.75 mm is determined.

2.3. Pull-Out Test

The pull-out test represents one of the biomechanical in vitro experiments, and it can be conducted on cadaveric bone, animal bone or artificial material. The objective of this analysis, which is conducted on swine ribs, is to determine the bearing capacity of the implant–bone system, i.e., the value of the pull-out force that will lead to the extraction of the mini-implant from the bone specimen [25].

Before experimental analysis of primary stability is performed, it is necessary to adequately prepare the specimen. When the bone scan is finished, the bone is placed on the steel implement specially designed for the needs of the experiment. The implement contains two L-profiles that demand very precise production. The bottom part of the implement has four holes, where the bottom surface of the swine rib is attached with four screws. In the production process, special care is taken on hole locations, which need to provide sufficient distance between the screws and the inserted mini-implant in order to preserve the bone’s structure. Self-drilling mini-implants are hand tightened in a perpendicular direction on the bone surface using a handheld screwdriver, as shown in Figure 4a. Therefore, the construction of the implement with necessary distances of holes provides a pure pull-out force without additional bending moments.

![Figure 4](image-url)

**Figure 4.** The insertion of the mini-implant into bone, with a 90° angle, through the hole in the implement (a), and the implement attached with fixed and movable parts of the testing machine (b).

Experimental research is performed with a universal digital machine for material testing, Zwick 143501 model (Zwick GmbH & Co., Ulm, Germany), with a force transducer U2A by the HBM (Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany) manufacturer. Specimens are placed into the testing machine via the implement. The bottom part of the implement, for which the swine rib is fixated, is placed in the bottom clamp of the testing machine. The upper part of the implement, via the upper clamp, is fixated to the movable part of the testing machine, where the force transducer is placed (Figure 4b).

Figure 5 gives a comparative representation of the experimental pull-out tests carried out on the 20 samples of both the Tomas®-pin and Perfect Anchor mini-implants, where the pull-out force-displacement results are shown.
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Figure 4.
The insertion of the mini-implant into bone, with a 90° angle, through the hole in the implement (a), and the implement attached with fixed and movable parts of the testing machine (b).

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Figure 5 gives a comparative representation of the experimental pull-out tests carried out on the 20 samples of both the Tomas®-pin and Perfect Anchor mini-implants, where the pull-out force-displacement results are shown.

It is noticeable that the Tomas®-pin mini-implant can handle greater pull-out forces with greater displacements before the implant is extracted from the bone.

Variances of pull-out force for subsamples do not have a significant difference \( p < 0.515 \). A statistically significant difference of mean for pulling forces between implants Perfect Anchor and Tomas®-pin is obtained \( p < 0.028 \) [3].

2.4. FEM Analysis

After obtaining all of the important geometric characteristics, according to the previously described procedure, 3D models of the mini-implants and the surrounding cortical and cancellous bone segments are created, with the CAD/CAM/CAE system CATIA. Cortical and cancellous bone segments are modelled as cylinders with a diameter of 7 mm, with a cortex thickness of 0.675 mm, which represents the average cortex thickness estimated by measuring. Then, the same models are imported into Abaqus software (V, Dassault Systèmes, Vélizy-Villacoublay Cedex, France, 2012), where their mechanical properties along with advanced surface contact features are implemented.

Material properties are expressed with Young’s modules of elasticity, Poisson’s coefficients and densities. Real material behaviour under load conditions were considered, where the titanium alloy Ti6Al4V is presumed to be homogeneous and isotropic, and cortical and cancellous bone are considered orthotropic [26–29]. Table 2 shows material properties of mini-implants and bone segments used for FEM analysis.

Figure 6a shows the 3D-designed implant–bone system with Tomas®-pin, and Figure 6b shows the 3D-designed implant–bone system with Perfect Anchor mini-implant.
Table 2. Properties of materials.

| Material/Properties | Ti6Al4V | Cortical Bone | Cancellous Bone |
|---------------------|---------|---------------|-----------------|
| Density [g/cm³]     | 4.510   | 1.94          | 0.55            |
| $E_{xx}$ [GPa]      | 105     | 11.30         | 0.3468          |
| $E_{yy}$ [GPa]      | 105     | 13.80         | 0.4572          |
| $E_{zz}$ [GPa]      | 105     | 19.40         | 1.1071          |
| $\nu_{xy}$         | 0.37    | 0.274         | 0.05            |
| $\nu_{yz}$         | 0.37    | 0.237         | 0.01            |
| $\nu_{zx}$         | 0.37    | 0.237         | 0.322           |

Figure 6. 3D-designed implant–bone system (a): Tomas®-pin and (b): Perfect Anchor.

FEM modelling is integrated in biomechanical research for the ability to reproduce behaviour of bones, joints or implants, and it is used as an alternative to in vitro experiments, which can be expensive and difficult to carry out [30,31]. The National Agency for Finite Element Method has defined the finite element stress analysis as a "theoretical method that can be used for calculating the behaviour of a real structure by performing algebraic
solutions of a set of equations describing idealized model structure with finite number of variables” [32].

Discretization of mini-implants and bone segments is performed with C3D4 elements, i.e., linear tetrahedrons with 4 nodes. The complete system used uniform mesh with a maximum size of finite elements of 0.2 mm. Thus, the structures of Tomas®-pin and Perfect Anchor mini-implants were discretized with 485,429 and 481,524 finite elements containing 86,477 and 83,154 nodes, respectively.

The movement of the bone’s outer surfaces is disabled, while the movement of the threaded surface of the mini-implant and contact surfaces of cortical and cancellous tissue was enabled only in the direction of implant length. The interaction between contact surfaces of the implant and bone is realized with surface-to-surface contact with finite sliding. The section of the mini-implant above bone surface is excluded, so that model is “less demanding” and precise location of pull-out force impact is simulated. The upper surface of the implant is coupled with a node, and concentrated force is applied on this node [33].

The comparative analysis between the two different mini-implant designs shows the magnitude of stresses within the implants and surrounding bone segments. The equivalent stress is considered because it represents a mean stress in its three components x, y and z directions [34].

3. Results

The pull-out simulation is performed by applying concentrated force with 5 N increments. The maximum pull-out forces that could be applied on the implant–bone system, along with the maximum Von Mises stresses and displacements, for both implant types are shown in Table 3.

Based on data from Table 3, it can be established that the Tomas®-pin can manage a greater pull-out force. Although Perfect Anchor manages lower pull-out forces on the contact zone between the implant and cortical bone, greater stresses are developed. This phenomenon is attributed to the impact of mini-implant geometry, and it can be explained by the fact that Tomas®-pin has greater thread core diameters and conicity regarding the Perfect Anchor.

Table 3. Analysis Results.

| Implant Type          | Tomas®-pin | Perfect Anchor |
|-----------------------|------------|----------------|
| Maximum concentrated force [N] | 216.9 | 163.1 |
| Maximum Von Mises stress [MPa] | 495.7 | 585.6 |
| Maximum displacement [mm] | 1.806 | 1.540 |

Each force increment gives information about the pull-out force-displacement ratio for certain load conditions. This way, pull-out test diagram is created, by which experimental results are verified. As in the case of experimental pull-out test diagram, linearity between the force increment and displacement level of mini-implant is noticed.

Figure 7a shows Von Mises stresses generated on the cortical bone for the system with Tomas®-pin. The maximum stress on the cortical bone amounts to 495.719 MPa. Additionally, the uniform distribution of greater stresses is noticed around the mini-implant insertion zone. Figure 7b shows Von Mises stresses generated on the cortical bone for the system with Perfect Anchor. The maximum stress on the cortical bone amounts to 585.625 MPa. Unlike the system with Tomas®-pin, there is no uniform stress distribution. In addition, this system generates bigger stress, and it only occurs in a specific zone, while the rest of mini-implant insertion zone is less loaded than in the previous case.
Figure 7. Von Mises stress generated on the cortical bone (a): Thomas®-pin and (b): Perfect Anchor.

Figure 8a shows Von Mises stresses generated on the Tomas®-pin mini-implant. The maximum stress occurs on implant thread coil and amounts to 998.556 MPa, which exceeds the yield strength of 880 MPa for Ti6Al4V material. The high-stress value on the thread coil is developed due to the high-stress concentration caused by the tiny and sharp thread coil. Figure 8 (top-right) shows a cross-section of the most stressed implant zone with the effects on the surrounding cortical bone. The nearby cortical bone cross-section has a maximum stress of 452.945 MPa, which means that the maximum cortical bone stress does not occur in the same location as the highest stress on mini-implant thread coil.

Figure 8c shows Von Mises stresses generated on the Perfect Anchor mini-implant. The maximum stress occurs on the implant thread coil and amounts to 1129.84 MPa, which exceeds the yield strength of 880 MPa for Ti6Al4V material. Same as in previous case, this is caused due to the high-stress concentration. Figure 8a,b shows a cross-section of the most stressed implant zone with the effects on the surrounding cortical bone. The nearby cortical bone cross-section has a maximum stress of 417.862 MPa, which means that the maximum cortical bone stress does not occur in the same location as the highest stress on the mini-implant thread coil.
Figure 8. Von Mises stress generated on the mini-implant thread coil (a,c) and cross-section of the most stressed implant zone with effects on the surrounding cortical bone (b,d); (a,b): Tomas®-pin and (c,d): Perfect Anchor.

Figure 9 shows the maximum displacements for the implant–bone system with finite elements meshes for Tomas®-pin (Figure 9a) and Perfect Anchor (Figure 9b).

Figure 10 shows a comparative pull-out diagram of Tomas®-pin and Perfect Anchor mini-implants along with the values obtained with FEM analysis. The force-displacement lines for FEM analysis end when analysis reaches the point of negative force increase, as it is noticeable in Figure 10. The average deviation between experimental and numerical results amounts to 1.834% for Tomas®-pin and 2.154% for Perfect Anchor.
Figure 9. Displacements of the bone-implant system (a): Tomas®-pin and (b): Perfect Anchor.

Figure 10 shows a comparative pull-out diagram of Tomas®-pin and Perfect Anchor mini-implants along with the values obtained with FEM analysis. The force-displacement lines for FEM analysis end when analysis reaches the point of negative force increase, as it is noticeable in Figure 10. The average deviation between experimental and numerical results amounts to 1.834% for Tomas®-pin and 2.154% for Perfect Anchor.
This study focused on the impact of the mini-implant design on primary stability. For examined specimens, cortex thicknesses were sufficient enough for successful implant insertion, which was important for conducting pull-out tests.

The obtained results show that the value of generated pull-out force, and therefore primary stability, depends on mini-implant geometry. The Tomas®-pin mini-implant attributed with greater core diameters, greater conicity and shorter thread length, regarding Perfect Anchor with a greater TSF factor, which showed the capability of managing greater pull-out forces. Therefore, core diameters, conicity and pitch of a thread have more impact on primary stability than thread length.

FEM analysis results show that the Perfect Anchor implant type in the implant–bone system generates greater stresses, although it reaches lower pull-out forces, compared to the Tomas®-pin implant type. In order to achieve favourable primary stability of the mini-implant (temporary anchorage device), careful selection of the implant system combined with adequate bone quality and a proper insertion protocol are strongly suggested to minimize the destructive influence of loading forces on the surrounding dental implant. This study integrated medical imaging, engineering design and analysis to develop an important tool for clinical orthodontics.

Further research should be based on optimizing the process of mini-implant geometry, which would result in increased primary stability, especially in managing greater loads and reducing generated stresses on the contact of the implant thread surface with surrounding tissues.

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