Original Article

Institution of MECHANICAL ENGINEERS

Journal of ENGINEERING IN MEDICINE

Proc IMechE Part H:
J Engineering in Medicine
2021, Vol. 235(9) 1046–1057

DOI: 10.1177/09544119211023630
journals.sagepub.com/home/pih
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# Finite element simulation and statistical investigation of an orthodontic mini-implant's stability in a novel screw design

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**Abstract**

One of the essential aspects of the mini-implant's successful application is its stability after being installed in the bone. The stability of the mini-implant affected the most by its geometry. In the present research, the effect of the geometry-related parameters of the mini-implant on its lateral displacement is investigated by Finite Element (FE) modeling using ABAQUS software. The parameters studied include length, diameter, pitch, and depth of the screw threads; besides, length and angle of the conical section. The Taguchi method was used to prevent many experiments. The mesh convergence tests and experimental tests confirmed the FE model quantitatively and qualitatively. Mean of means and variance analysis determined the parameters significance and their contribution on the stability. The screw diameter and length have the most contribution to mini-implant' displacement. The effect of screw pitch was less than that for length and diameter. The conical section improved the initial stability by creating compressive stress and additional friction in its surrounding bone. No significant effects on the stability of the mini-implant have been observed for the non-threaded part. By examining the effect of thread depth on its stability by defining the ratio of thread depth to the internal diameter and to maintain the strength of the screw the optimal value for internal to external ratio is set at about 0.7.

**Keywords**

Mini-implant's stability, screw geometry, finite element simulation, Taguchi method, variance analysis

Date received: 15 March 2021; accepted: 17 May 2021

## Introduction

Mini-implant is one of the essential tools in orthodontic treatment. These tools are tiny screws with a maximum diameter of 2 mm and an approximate length of 10 mm. They are installed in the jawbone between the teeth roots to serve as anchorage for the applied forces. These screws show their best performance when they remain firmly in place without displacement. The mini-implant stability depends on various biological and mechanical factors. The mini-implant geometry is one of the most critical mechanical factors. The stability assessment is usually performed by measuring lateral displacement when the forces are applied. The lower the displacement, the higher its stability.[1]

The clinical success in the use of mini-implants is above 80%[2]; however, failure cases are reported.[3] Many unsuccessful uses of mini-implants appear in the very early stages of placement and loading. Therefore, the primary stability is very crucial. Primary stability is achievable by optimizing the shape and geometry of the screw.[4]

Factors that affect the stability are the bone quality, position, and geometry of the screw. The geometry-related parameters are the length, diameter, shape (conical or cylindrical), pitch, and thread shape.[5] In this regard, McNally et al.[6,7] recommended screws larger

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than 1.8 mm in diameter, but emphasized that an excessive increase in diameter would cause damage to tissues and bones. Abdelgader et al.[8] showed that with increasing the pitch, the generated stresses increase heterogeneously with destructive effects. It is revealed that conical and deep threads decrease the required torque and are easier to install than cylindrical ones. However, they have little effect on the created strains, and damage the bone by increasing the stresses around it.[3,8]

The changes in the mini-implant design should be made with caution because the mechanical methods of controlling the stability are not accurate.[9,10] To solve this problem non-destructive mechanical methods such as FE analysis are used. Previous research on the effect of geometry-related parameters revealed that the performance and stability of mini-implant generally affected by length,[10–14] screw diameter,[10,11,13] screw shape (conical or cylindrical),[12,15,16] thread shape,[4,8,13,17] screw pitch,[18] and thread depth.[13,19] Theses parameters were studied individually or in combination with two or three parameters.

The mini-implant insertion inside the bone is temporary and the stability of a proper retention is very important. For each new mini-implant design, it is necessary to measure the stability by experimental methods. For this purpose, in recent years, various invasive methods like insertion torque analysis[20] and pull-out test,[21] and non-invasive methods like radiographic and finite element analysis[22] have been used in the references. Among the mentioned methods, measuring the insertion torque is one of the common methods.[23]

The aim of this study is to investigate the effect of geometric parameters of mini-implants in a new proposed design on its lateral stability through finite element simulation and experimental tests. The intersection properties of mini-implant and bone are not fully understood and there is limited study in the field. We had to consider the intersection as osseointegrated, which is somehow the best assumption. There is no comprehensive research investigating the combined effect of geometry-related parameters on the mini-implant stability. The interdependencies of these parameters in mini-implant design have not been studied in detail or systematically. Therefore, in this study, the FE analysis was used as a non-destructive mechanical method to predict the mini-implant stability. Since the number of significant geometry-related parameters is large and too many tests are required, the Taguchi method was used as a solution to reduce the number of required tests.

## Materials and methods

### *Design of mini-implant*

A better screw-bone engagement is established by proper selection of the geometry-related parameters of the mini-implant, leading to an increase in the mini-implant primary stability. Such parameters include length, diameter, pitch, thread shape, and thread depth. Given the advantages of conical-shaped mini-implant, there are other parameters like the length and angle of conical part affecting the stability. In a novel proposed design, the primary role of the cortical bone, which must be engaged with a conical screw to create compressive stress is considered. The non-threaded part is another part that is included in the design located before the conical part. This part has two parameters: length and its angle with respect to the screw axis. It enters to the bone following the conical section when tightening the screw; thus, it will create compressive fitting. Figure 1(a) is depicted to show the design of the screw and the related parameters.

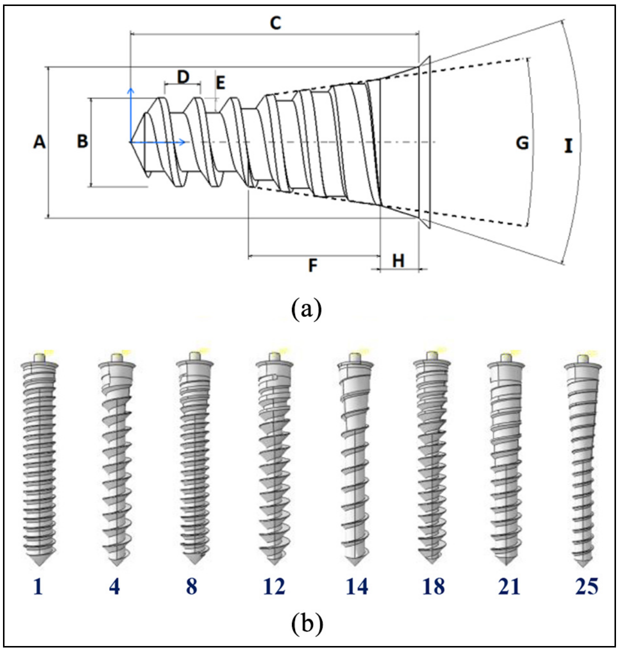


**Figure 1.** (a) The new design of screw and corresponding parameters: A-external diameter, B-internal diameter, C-the length of the mini-implant inside the bone, D- screw pitch, E-thread depth, F-conical part length, G-conical part angle, H-length of the non-threaded part, and I-the angle of the non-threaded part. (b) Some designed models (the numbers below the models show the designed experiment number according to Table 4).

As mentioned earlier, the external diameter should not exceed 1.8–2 mm, so that it has no intersection with the roots of adjacent teeth.[17] Thread depth is defined as the ratio of (E/B) to prevent excessive reduction in internal diameter and its strength. In conical section, the depth of threads gradually decreases from the cylindrical part until the non-threaded part, approaching zero at the beginning of the non-threaded part. Each parameter mentioned above is considered as one of the design factors of the Taguchi test with specific levels.

### *Design of experiments (DOE)*

Two test designs were used in the author's previous research: (1) the internal diameter of screw (B) as one of

**Table 1.** Levels of parameters tested in the first series of tests.[24]

| Factor | Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|---|
| B | 1 | 1.4 | | |
| C | 8 | 9 | 10 | 11 |
| D | 0.55 | 0.7 | 0.85 | 1 |
| F | 1 | 2 | 3 | 4 |
| G | 0 | 2 | 4 | 6 |
| H | 0.2 | 0.4 | 0.6 | 0.8 |
| I | 0 | 2 | 4 | 6 |
| E/B | 0.1 | 0.15 | 0.2 | 0.25 |

**Table 2.** Levels of parameters tested in the second series of tests.[24]

| Factor | Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|---|
| A | 1.2 | 1.4 | 1.6 | 1.8 |
| C | 8 | 9 | 10 | 11 |
| D | 0.55 | 0.7 | 0.85 | 1 |
| F | 1 | 2 | 3 | 4 |
| G | 0 | 2 | 4 | 6 |
| H | 0.3 | 0.6 | | |
| I | 0 | 2 | 4 | 6 |
| E/B | 0.1 | 0.15 | 0.2 | 0.25 |

the test factors, and (2) the external diameter of screw (A) as one of the test factors. The remaining factors were considered the same.[24] In the first series of tests, the levels of B were selected in a way that the value of A did not exceed 2 mm as the (G) and (I) are increased. The maximum value of B was approximately 1.4 mm. The levels of each factor in the first series of tests are listed in Table 1.

In the second series, the external diameter (A) has considered as one of the Taguchi's factors. The internal diameter of the screw is a function of other longitudinal, diagonal, and angular parameters. Table 2 provides the levels of each parameter.

The results of these experiments have been extracted and analyzed.[24] They indicated that the screw length and diameter have the most significant effect on the stability, and the effect of other parameters is insignificant. In this paper, new tests are designed in which the screw length and diameter are removed and their effect is ignored. Only six parameters are considered, including (F), (H), (G), (I), (D), and (E/B). The screw length and external diameter was considered 11 and 1.8 mm, respectively, and only the remaining parameters are varying. The parameters and their levels are provided in Table 3. According to Table 3, the number of geometric parameters is six and each of the parameters is examined at five different levels.

Given the multiplicity of factors and their levels, the total number of experiments is five,[6] and performing all these experiments is not applicable. The factorial experiment design should be used. It is concluded that DOE can play a major role in the design of implants.[25]

**Table 3.** Levels of parameters tested in the new series of tests.

| Factor | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|---|
| D | 0.5 | 0.625 | 0.750 | 0.875 | 1 |
| F | 1 | 1.75 | 2.5 | 3.25 | 4 |
| G | 0 | 2 | 4 | 6 | 8 |
| H | 0.15 | 0.3125 | 0.475 | 0.6375 | 0.8 |
| I | 0 | 2 | 4 | 6 | 8 |
| E/B | 0.1 | 0.14 | 0.18 | 0.22 | 0.26 |

**Table 4.** The $L_{25}$ orthogonal array used in the new test design and its combined tests.

| Experiment number | F | G | H | I | D | E/B |
|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0.1500 | 0 | 0.500 | 0.10 |
| 2 | 1 | 2 | 0.3125 | 2 | 0.625 | 0.14 |
| 3 | 1 | 4 | 0.4750 | 4 | 0.750 | 0.18 |
| 4 | 1 | 6 | 0.6375 | 6 | 0.875 | 0.22 |
| 5 | 1 | 8 | 0.8000 | 8 | 1.000 | 0.26 |
| 6 | 1.75 | 0 | 0.3125 | 4 | 0.875 | 0.26 |
| 7 | 1.75 | 2 | 0.4750 | 6 | 1.000 | 0.10 |
| 8 | 1.75 | 4 | 0.6375 | 8 | 0.500 | 0.14 |
| 9 | 1.75 | 6 | 0.8000 | 0 | 0.625 | 0.18 |
| 10 | 1.75 | 8 | 0.1500 | 2 | 0.750 | 0.22 |
| 11 | 2.5 | 0 | 0.4750 | 8 | 0.625 | 0.22 |
| 12 | 2.5 | 2 | 0.6375 | 0 | 0.750 | 0.26 |
| 13 | 2.5 | 4 | 0.8000 | 2 | 0.875 | 0.10 |
| 14 | 2.5 | 6 | 0.1500 | 4 | 1.000 | 0.14 |
| 15 | 2.5 | 8 | 0.3125 | 6 | 0.500 | 0.18 |
| 16 | 3.25 | 0 | 0.6375 | 2 | 1.000 | 0.18 |
| 17 | 3.25 | 2 | 0.8000 | 4 | 0.500 | 0.22 |
| 18 | 3.25 | 4 | 0.1500 | 6 | 0.625 | 0.26 |
| 19 | 3.25 | 6 | 0.3125 | 8 | 0.750 | 0.10 |
| 20 | 3.25 | 8 | 0.4750 | 0 | 0.875 | 0.14 |
| 21 | 4 | 0 | 0.8000 | 6 | 0.750 | 0.14 |
| 22 | 4 | 2 | 0.1500 | 8 | 0.875 | 0.18 |
| 23 | 4 | 4 | 0.3125 | 0 | 1.000 | 0.22 |
| 24 | 4 | 6 | 0.4750 | 2 | 0.500 | 0.26 |
| 25 | 4 | 8 | 0.6375 | 4 | 0.625 | 0.10 |

Taguchi method is one of the most common methods for designing the factorial test.[26] The $L_{25}$ orthogonal array was used for the levels shown in Table 4.

According to Taguchi's design of experiments, the FE simulations were done and lateral displacement was determined. The obtained results were analyzed by Minitab software. The results were converted to the ratio of signal to noise according to the "optimum value-minimum value" strategy. Then, the mean of responses to the levels of factors were plotted by which the effect of each parameter on the mini-implant stability will be compared. It should be noted that, in the present research, the lateral displacement of mini-implant has been used as the stability criterion. The minimum displacement is equal to the maximum value of stability and is considered as the optimal condition. With analyzing the variance of responses, each parameter's contribution to the stability has been determined.

**Table 5.** Material properties.

| Material | Poisson's ratio | Young's modulus (MPa) |
|---|---|---|
| Mini-implant (Ti-alloy) | 0.3 | 102,000 |
| Cortical bone | 0.35 | 9000 |
| Cancellous bone | 0.3 | 700 |

### *Modeling and finite element simulation*

According to the designed experiments, models have been designed as a combination of cylinder and two frustums (conical and non-threaded part) with definite diameter and angle. Figure 1(b) shows some of the models. The length and diameter of these samples are the same, and the remaining dimensions are listed in Table 3.

The bone block, with an area of $10 \times 10\,mm^2$ composed of cortical and cancellous parts. The thickness of the cortical bone is 2 mm, and its height was 2 mm longer than the mini-implant length. The homogeneous, isotropic, solid materials were defined for all the elements and the model. The Young's module and Poisson's ratio of each material were assumed to be the same as the previous work according to Table 5.[24]

Based on the FE simulation results obtained by Lin et al.,[13] the frictional conditions have an insignificant effect on the mechanical behavior and stability of the mini-implant. Therefore, all contact surfaces were defined as frictionless in order to optimize the calculation efforts. A force has been applied as a point load parallel to the cortical bone and at the end of the mini-implant head. The loading was increased linearly from 0 to 2 N.

The meshing of the models was generated automatically by defining the node spacing on the sides of bone block and mini-implant. The node spacing and the optimal dimensions of elements were selected based on the convergence test of elements. The size of elements was selected so that the threads and their curves are covered accurately and adequately. The elements are of 4-node linear tetrahedral types. Because of the complicated and curved geometry of threads' location, this mesh type was only applicable. Figure 2(a) shows the generated mesh for one of the models. It is evident that the cortical bone elements are so finer than the cancellous part of the bone. This is due to the more significant effect of cortical bone in providing support anchor and creating the stresses. So, it should be included in the calculations with higher precision. Figure 2(b) presents contours of displacement distribution of one model after being analyzed.

Given the simplifications used in the simulation, which is common, simulations' validity should be evaluated using experimental tests in the same conditions. To this end, some samples (Figure 3(a)) with different geometries were first modeled and simulated. The lateral displacement of screws (installed inside the polyethylene block) was measured experimentally according to international standards[23] using a digital dynamometer and a dial indicator with a precision of 0.01 mm. The maximum torque required for installing each screw was measured using a torque meter in a polyethylene block. The steps of performing experimental tests are shown in (Figure 3(b) and (c)).

## Results

### *Mesh convergence and validation of FE simulation*

Mesh convergence is the first step to achieve the correct results in the FE method. For this purpose, some models with different numbers of elements were loaded. The displacement in terms of the number of nodes of the cortical bone's edge is presented in Figure 4 for tests 1–4. With increasing the number of nodes (reducing the element length), in the same loading conditions, the mini-implant displacement is converged to a specific value after 50 nodes along the edge of the cortical bone. As a result, in the present research, the edge of models

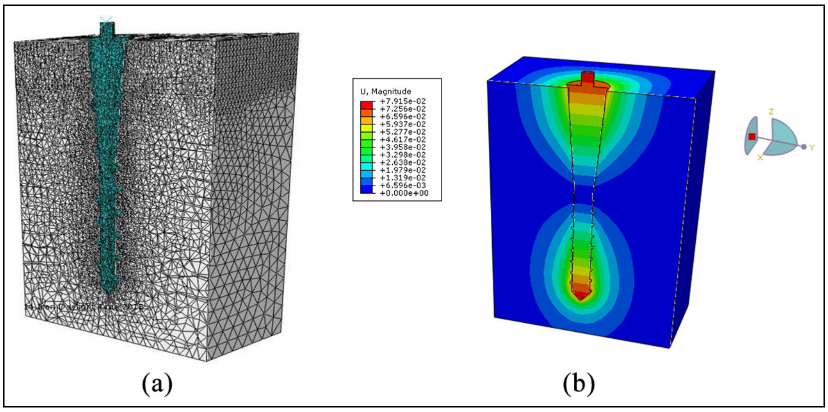


**Figure 2.** (a) The meshing used in one of the simulations and (b) displacement distribution contour of the mini-implant and bone during the loading.

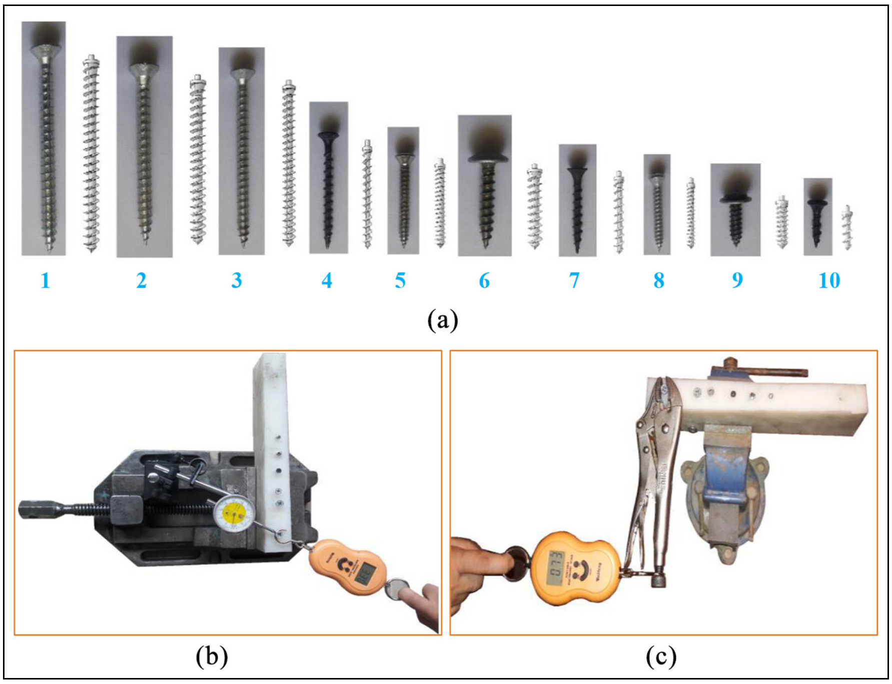


**Figure 3.** (a) Tested screws and their models, (b) how measuring displacement, and (c) how measuring the maximum install torque of each screw in the polyethylene block.

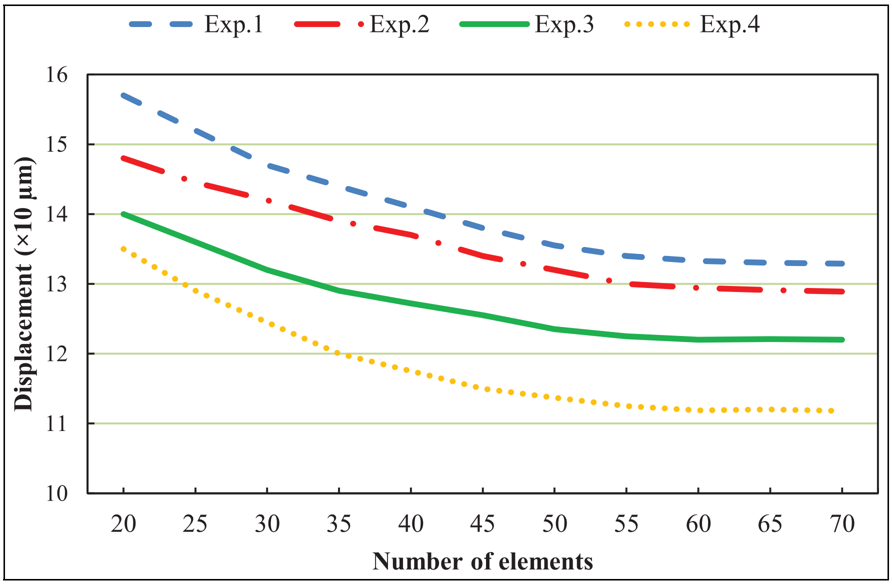


**Figure 4.** Results of simulations in terms of the number of elements on the edge of the cortical bone.

has been divided into 50 nodes; that is, each element has a length of 0.2 mm.

Figure 5(a) presented the lateral displacement obtained from FE simulation and that measured by a digital dynamometer and a dial indicator (the horizontal axis has been arranged in order of stability decrease). By comparing the primary displacement results obtained from numerical and experimental tests, it was found that the models have a high convergence. Besides, it was observed that in most models, the value measured from experimental tests is higher than that obtained from the numerical simulation. The main reason for this may be attributed to neglecting the computational errors and the conditions of polyethylene block-screw osseointegration[27,28]; in the modeling, it has been assumed that this contact surface is fully sticking, while in the experimental test, it is not valid.

The maximum torque for installing each screw inside the polyethylene block and the lateral displacement from simulations are shown in Figure 5(b) in order to validate the simulation results. It is evident that the more the torque required for installing the mini-implant

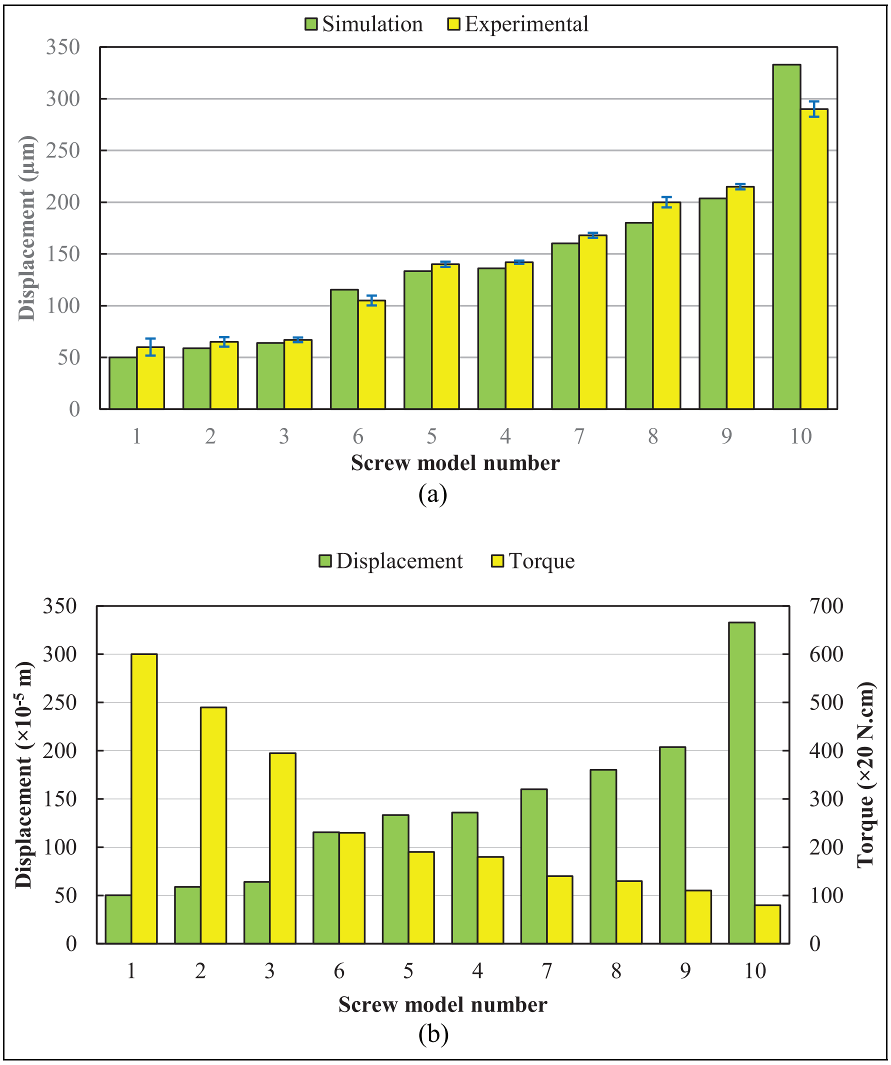


**Figure 5.** (a) Comparison of lateral displacement of screw head obtained from simulation and experimental test and (b) displacement of model's head and the maximum installation torque in the polyethylene block.

in the bone the more is its higher stability. According to Figure 5(b), the more the maximum installation torque in the polyethylene decreases, its lateral displacement and stability will increase and decrease, respectively. Qualitatively, there is a good agreement between the results of modeling and simulation, indicating that the FE test results are valid.

## *Analysis of mean of means*

As the FE simulation is done, the obtained results (displacement of mini-implant head) were imported to Minitab software, and the mean of responses were analyzed. Figure 6 is depicted to show the mean responses of levels of tested parameters.

The results obtained from analyzing the mean of results indicate that the minimum displacement and maximum stability occur at the conical part's length of 2.5 mm. With an increase in the length of the non-threaded part, the displacement and stability are reduced and increased, respectively. The reason for this is due to the non-varying external diameter of the screw. As the angle of the conical part increases, the internal diameter and contact surface are both decreased. The increased displacement resulting from the increased pitch of the mini-implant is justified with a reduced area of the mini-implant-bone contact surface. As a result, the stability of the mini-implant was reduced. Similar results of the effect of screw pitch on the mini-implant stability have been reported in previous works.[18] As the thread depth increases, the mini-implant-bone contact surface increases and positively affects engagement and stability. However, the excessive increase in the thread depth leads to a reduction in the screw's internal diameter and a reduction in its shear strength against the force it applies inside the bone.

From the results, it seems that existence of non-threaded and conical parts has negative effects on the stability of the mini-implant; however, this is valid only if the external diameter of the screw is constant. Therefore, the conical part not only creates additional

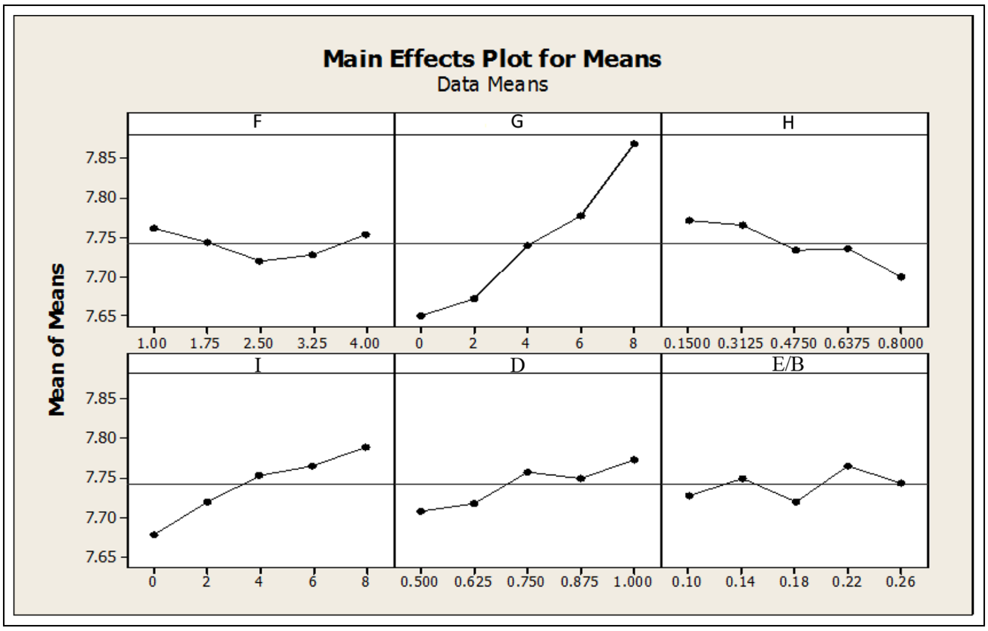


**Figure 6.** The mean response of tests in terms of the level of parameters in the new tests.

compressive stress around the screw, but also with increasing the engagement and the contact surface of the mini-implant-bone, it will increase its primary and secondary stability. It should be noted that the area of the contact surface of the screw-bone, in general, has a direct relationship with its stability.

### *Analysis of variance*

In this research, the variance analysis is used to investigate the effect of each geometric parameter of the mini-implant (mentioned earlier) on its stability. Using this method, *p*-value is calculated to determine significance of each parameter's effect on the response and its contribution. The variance analysis of the results is provided in Table 6.

Table 6 shows the contribution of each tested parameter. The angle of the conical part has the maximum effect on displacement of the mini-implant (about 65%), indicating the significance of the angle in increasing the mini-implant stability; however, comparing to the length and diameter of the screw, the effect of angle is less. Besides, the angle of the non-threaded part, with a contribution of nearly 6%, plays an important role in controlling mini-implant stability. Finally, other parameters have an effect on the control of the mini-implant lateral displacement.

Since the error has zero degrees of freedom, performing a complete variance analysis in Table 6 is not possible, and *p* and *F* values are not calculated. Another test, (26th one), with the same levels was performed that was not included in the Taguchi test. By using this technique, the remaining error's degree of freedom is changed from 0 to 1. Then, the complete variance analysis was performed for the most optimistic case. The combination of parameters of the 26th test is in accordance with Table 7. Besides, the results of the second variance analysis are listed in Table 8. The results of the modified variance analysis indicated that all parameters with $p < 0.05$ have meaningful and valid results.

**Table 6.** The variance analysis of the displacement of the mini-implant head.

| Factor | DF | Seq SS | Adj MS | % |
|---|---|---|---|---|
| F | 4 | 0.006136 | 0.001534 | 2.6 |
| G | 4 | 0.152696 | 0.038174 | 64.8 |
| H | 4 | 0.016696 | 0.004174 | 7.1 |
| I | 4 | 0.038016 | 0.009504 | 16.2 |
| D | 4 | 0.015376 | 0.003844 | 6.5 |
| E/B | 4 | 0.006616 | 0.001654 | 2.8 |
| Error | 0 | - | - | - |
| Total | 24 | 0.235536 | | 100 |

**Table 7.** Combination of 26th test.

| Factor | Length | Diameter | F | G | H | I | D | E/D |
|---|---|---|---|---|---|---|---|---|
| | 11 | 1.8 | 4 | 1.6 | 0.15 | 2 | 0.75 | 0.1 |

## Discussion

In this section, the average signal to noise ratio has been converted to a value of displacement for better interpretation. Figure 7 shows the displacement variations of mini-implant head in terms of length and diameter compared to the first and second tests in Haghighi et al.[24] It is evident that, with every 0.1 mm increase in the

**Table 8.** Results of modified variance analysis.

| Factor | DF | Seq SS | Adj MS | *F* | *p* |
|---|---|---|---|---|---|
| F | 4 | 0.0076521 | 0.0015482 | 774.10 | 0.027 |
| G | 4 | 0.1543916 | 0.0383343 | 19167.14 | 0.005 |
| H | 4 | 0.0164791 | 0.0042831 | 2141.54 | 0.016 |
| I | 4 | 0.0383003 | 0.0095792 | 4789.59 | 0.011 |
| D | 4 | 0.0154867 | 0.0038717 | 1935.84 | 0.017 |
| E/B | 4 | 0.0067463 | 0.0016866 | 843.38 | 0.026 |
| Error | 1 | 0.0000020 | 0.0000020 | | |
| Total | 25 | 0.2388154 | | | |

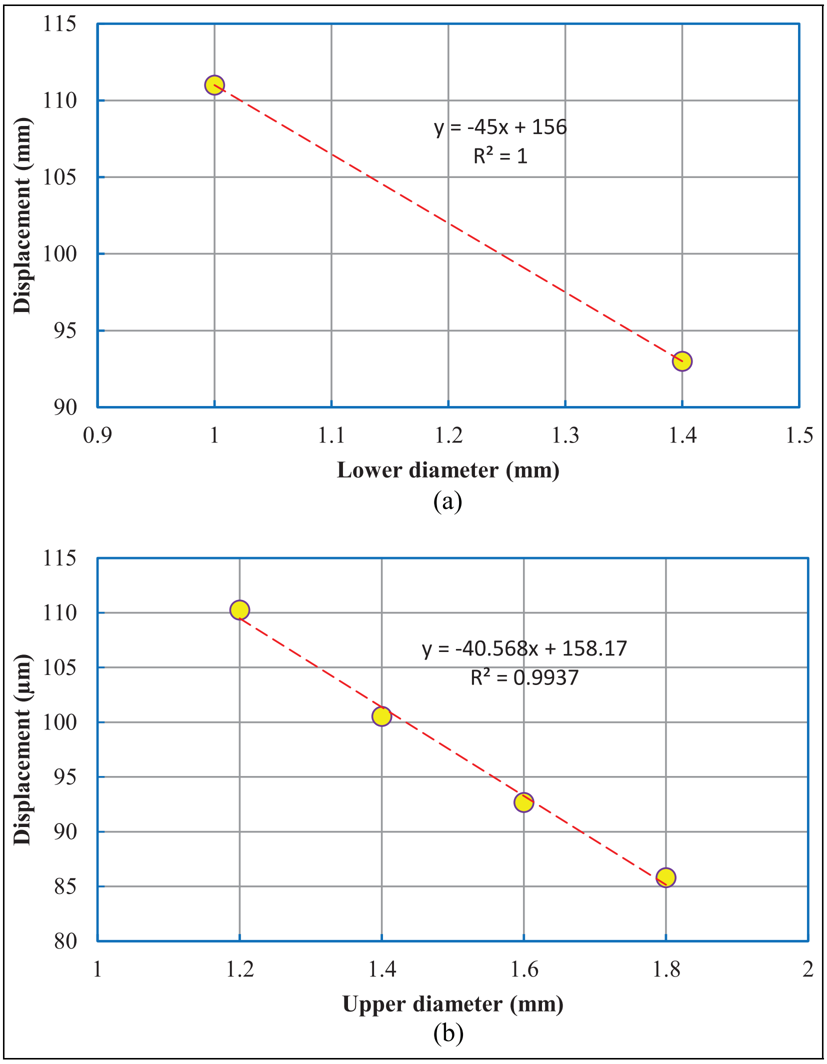


**Figure 7.** Displacement of the mini-implant head in terms of: (a) external diameter and (b) internal diameter according to the results obtained in Haghighi et al.[24]

internal diameter, the mini-implant displacement reduces by 4.6 mm. Besides, with every 0.1 mm increase in the external diameter, the mini-implant displacement reduces by 4.1 mm; accordingly, screw stability will increase with the same ratio.

According to the linear fitting shown in Figure 8, with every millimeter increase in mini-implant length, displacement of its head reduces by 6.6 µm (according to the first test) and 7.4 µm (according to second test); as a result, its stability has increased with the same ratio. It is clear that every increase in diameter is more significant than that of length. A large part of the mini-implant length is engaged with the cancellous bone. Because of the high softness and low Young's module,

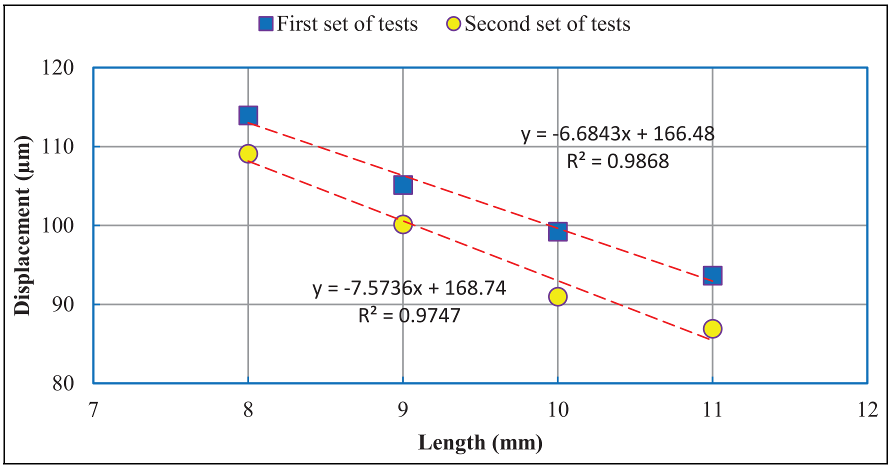


**Figure 8.** Displacement of the mini-implant head in terms of its length according to the results obtained in Haghighi et al.[24]

this part is not suitable support for the mini-implant. With the use of this mechanism, the effect of an increase in length will reduce compares with that of diameter.

The conical part is the other geometrical parameter included in present research by modifying the mini-implant geometry to increase its stability. Conical part located in the upper half part of screw engaging with cortical bone. This conical frustum includes two factors of angle and its length along the screw axis. In the results of the new test series, the conical part parameters are meaningful but not valid; because the contribution of the conical part length is less than that of the first series of tests. So, the results of the first set of tests are more credible. The effect of the conical part angle in the third step of tests is not credible because of the same reason. In this step, the screw diameter is constant, and increasing the conical part angle only affects the bone-metal contact area, which reduces this area in the cylindrical parts of the screw. It is evident that as the contact surface is decreased, the stability is decreased.

The mini-implant displacement decreases as the conical part angle and length are increased; thus, its stability is increased. Displacement of the mini-implant head in terms of parameters of conical part is plotted in Figure 7. Because of the better results of variance analysis, the average results of signal to noise ratios in Figure 9 have been converted to the mini-implant displacement. According to the linear fitting of data shown in Figure 9(a), it is observed that with each millimeter increase in the length of non-threaded part, displacement of the mini-implant head reduces by 2.34 µm. By comparing the lateral displacement of mini-implant with each millimeter increase in the parameters of length, diameter, and the conical part length, it is observed that conical part length effect is less than two other parameters in controlling the displacement. Besides, it is observed that the conical part length has a direct relation with the contribution. According to the linear fitting shown in Figure 9(b), it can be found that with every degree increase in conical head angle, the mini-implant displacement decreases by 1.8 µm. As a result, the effect of conical part length and angle is less than the screw length and diameter. The conical part increases its primary stability by creating additional compressive stress in the surrounding bone of the mini-implant.

The effect of length and angle of the non-threaded part is similar to the conical part. It will increase the stability by creating compressive fitting between screw and bone. The parameters of the non-threaded part have not shown a meaningful variance analysis. It is concluded, that the non-threaded part has an insignificant effect on the final stability.

Thread depth and pitch are the essential factors in the mini-implant stability. Their effect has been clearly determined. These two parameters increase the primary and secondary stability by increasing the area of the contact surface and screw-bone engagement. The fitted displacement of mini-implant in terms of screw pitch and thread depth ratio in all three steps of the test are presented in Figure 8.

Figure 10(a) shows a linear model of fitting data of displacement in terms of screw pitch. This figure indicates that with every 0.1 mm increase in screw pitch, it's lateral displacement decreases from 0.13 µm (in third step test) to 0.22 µm (in first step test). As a result, the higher primary stability level of mini-implant is obtained for lower screw pitch. Figure 10(b) shows the displacement variations of mini-implant obtained from the average signal-to-noise ratios in terms of thread depth fitted with a linear model. Based on the linear equations of this plots, the results of the first and second steps of tests have a proper and meaningful relationship with the linear model. The results show that, with every 0.05 increase in the thread depth to diameter

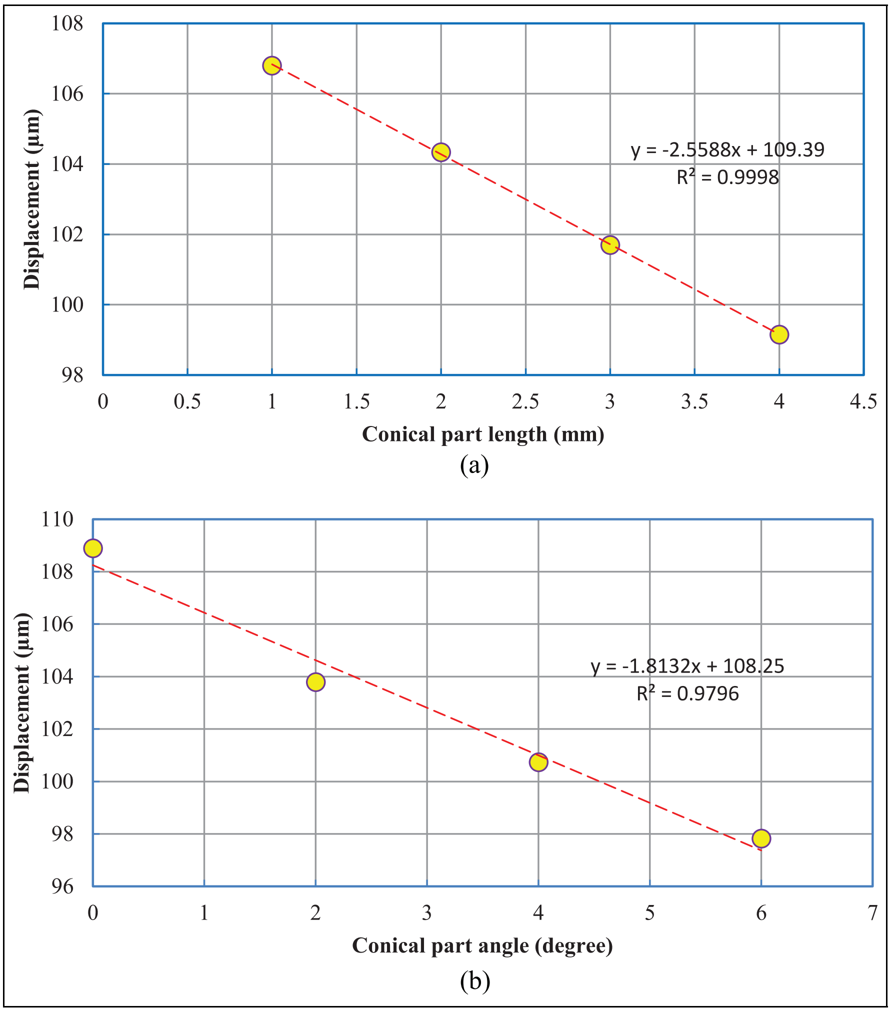


**Figure 9.** Displacement of mini-implant in terms of: (a) angle and (b) length of the conical part.

ratio, the lateral displacement increases by 0.29–0.34 µm; on the other hand, its final stability decreases by the same ratio. Despite increasing the thread depth, decreases the mini-implant stability, it should be noted that as its internal diameter decreases, the strength of its screw reduces, and it is more likely to be yielded. So, according to the results of the third step of tests and the results of the previous research,[19] the optimal ratio of internal to external screw diameter was determined as 0.7.

## Conclusions

In the present research, by some modifications in the screw design, the effect of mini-implant geometry-related parameters on its stability is investigated. Screw diameter and length have the highest effect on stability control. With each millimeter increase in the screw's diameter and length, its lateral displacement decreases by (40–46) µm, and (6.6–7.4) mm, respectively, and as a result, the stability increases. The conical section of the mini-implant was defined by its angle and conical length. The conical section improved the initial stability by creating compressive stress and additional friction in its surrounding bone. The lateral displacement decreased by 2.3 and 1.8 mm with increasing each millimeter and each degree in the conical section's length and angle, respectively. The length and angle of the non-threaded part do not significantly control the lateral displacement. The higher the pitch of the mini-implant, the lateral displacement increases by 1.3–2.2 µm. It is necessary to consider the minimum possible value for the pitch according to the threads' shape. With increasing the ratio of internal to external diameter, the screw-bone contact surface increased, and the stability increased. However, considering limits for this ratio seems necessary to maintain the strength of the screw. The optimal value for this ratio is set at about 0.7.

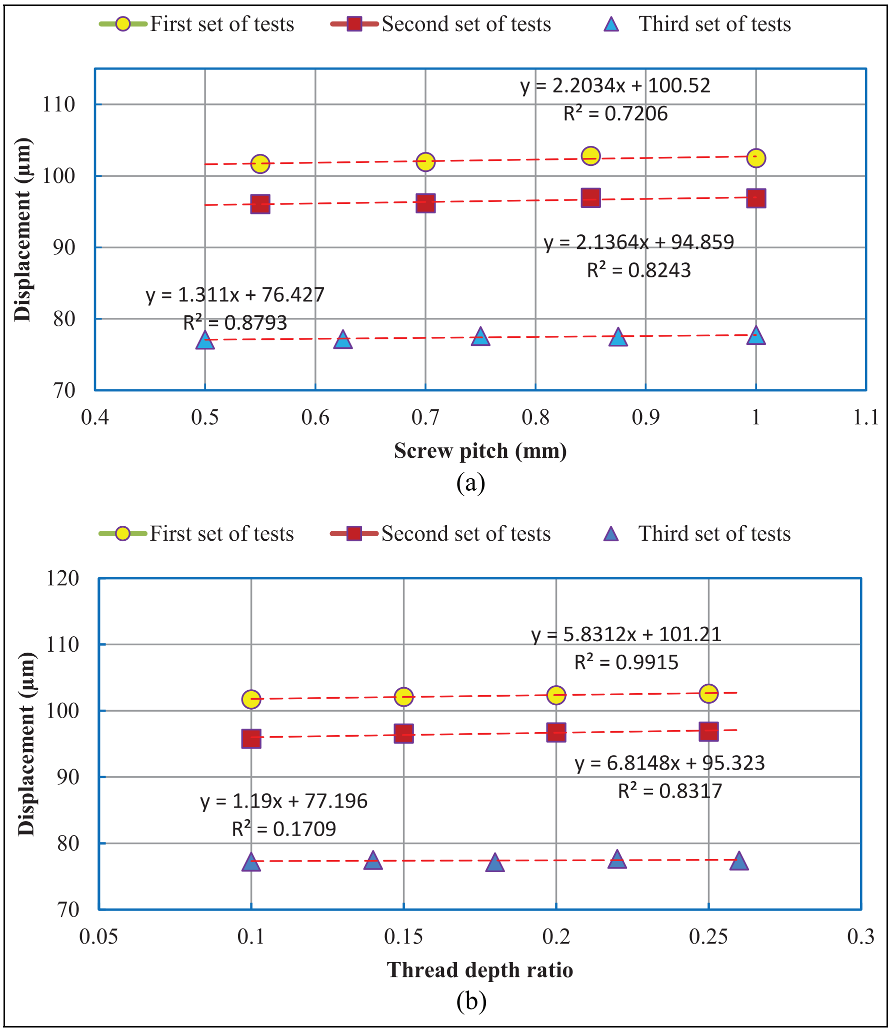


**Figure 10.** Displacement of mini-implant in terms of: (a) screw pitch and (b) thread depth to diameter ratio.

## Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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