Original Article

Optimal force magnitude loaded to orthodontic microimplants: *A finite element analysis*

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ABSTRACT

Objective: To find an optimal force that can be loaded onto an orthodontic microimplant to fulfill the biomechanical demands of orthodontic treatment without diminishing the stability of the microimplant.

Materials and Methods: Using the finite element analysis method, 3-D computer-aided design models of a microimplant and four cylindrical bone pieces (incorporating cortical bone thicknesses of 0.5, 1.2, 2.0, and 3.0 mm) into which the microimplant was inserted were used. Various force magnitudes of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 N were then horizontally and separately applied to the microimplant head as inserted into the different bone assemblies. For each bone/force assembly tested, peak stresses developed at areas of intimate contact with the microimplant along the force direction were then calculated using regression analysis and compared with a threshold value at which pathologic bone resorption might develop.

Results: The resulting peak stresses showed that bone pieces with thicker cortical bone tolerated higher force magnitudes better than did thinner ones. For cortical bone thicknesses of 0.5, 1.2, 2.0, and 3.0 mm, the maximum force magnitudes that could be applied safely were 3.75, 4.1, 4.3, and 4.45 N, respectively.

Conclusions: For the purpose of diminishing orthodontic microimplant failure, an optimal force that can be safely loaded onto a microimplant should not exceed a value of around 3.75–4.5 N. (*Angle Orthod.* 2016;86:221–226.)

KEY WORDS: Optimal force; Orthodontic microimplant

INTRODUCTION

Since 1997, incorporation of orthodontic microimplants (OMIs) into daily practice has dramatically optimized treatment planning, acting as a virtual savior of situations demanding absolute anchorage. However, they are still being researched for the purpose of improving their prognosis and diminishing reported high failure rates.[1,2]

As their primary retention in bone is mainly a mechanical one, and—unlike conventional dental implants that depend ultimately on osseointegration for their stability—any disruption of the OMI/bone interface in the form of bone microdamage might negatively affect the primary stability of these devices and consequently lead to loosening or even failure. Such microdamage can result from the accumulative stresses of either insertion of the microimplants or later biomechanical implications, especially if these stresses are beyond the bone's threshold.

In fact, the development of such stresses around the microimplant is of multifactorial origin, among which orthodontic force has been postulated as one.[3–5] Because OMI failure has been reported to occur predominantly during the first 3–4 months after insertion[4,6] and, as orthodontic forces are currently loaded immediately, failure might be attributed to the latter. The stability of a microimplant in bone depends on its intimate press-fitting without loosening or displacement. Liou et al.[7] found significant screw displacement after applying immediate forces of

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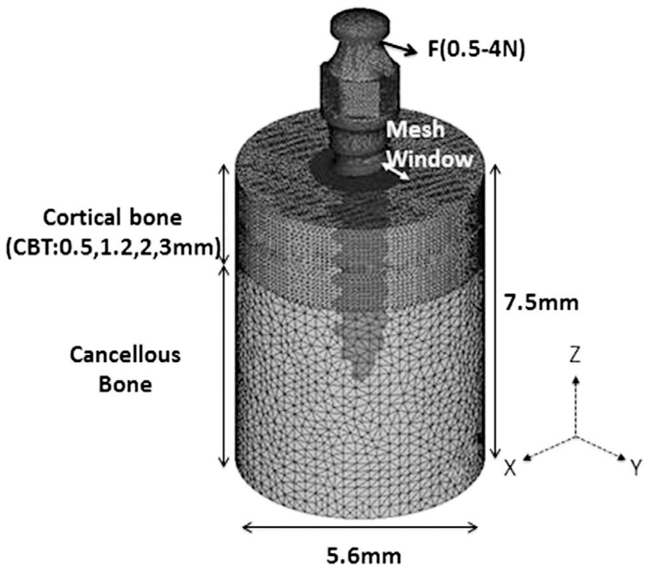

Figure 1. Geometric assembly of OMI and bone specimens used in the study after meshing step, with mesh window shown for the cortical bone and the force (F) applied along the y-axis.

400 g. Others found displacement to occur at even lower force levels.[8,9] Wang et al.[10] found that screw displacement was not correlated with force magnitudes of 200 g to 425 g and that beyond this range, other consequences might ensue. When an excessive load is applied, partly osseointegrated microimplants can become extremely mobile and eventually fail.[4] For this reason, it is essential during treatment to set a maximal force magnitude that can be loaded safely onto the OMIs to fulfill the biomechanical requirements without affecting microimplant stability.

Therefore, the aim of this finite element (FE) analysis method-based study is to find an optimum force magnitude for loading onto OMIs by analyzing the developed compressive stresses in the bone area near the microimplant.

MATERIALS AND METHODS

The concept in performing this study was to relate different force magnitudes added to OMIs inserted into bone to the resulting compressive radial stresses developed at the cortical bone area contacting the microimplant along the compressive side and then comparing the peak of these stresses to a threshold value at which pathologic bone resorption might occur. As it is now well-established that cortical bone thickness (CBT) is considered a major determinant of microimplant retention, the impact of forces was analyzed relative to different CBTs. Based on our previous study,[11] 3-D CAD models of titanium alloy–based OMIs and a cylindrical bone piece 7.5 mm in height and 5.6 mm in diameter were established

Table 1. Material Properties Used in the Study

Material	Young's Modulus (GPa)	Poisson's Ratio	Ultimate Strength (MPa)
Cortical bone	13.7	0.3	198.2
bone	1.37	0.3	
Titanium alloy	113.4	0.342	

(Figure 1) and exported to FE software (Deform v6.1, Scientific Forming Technologies, Columbus, Ohio). The OMIs were No. SH 1413-07, having a small head, 1.4-mm neck diameter, 1.3-mm tip diameter, and a 7-mm length (Absoanchor, Dentos Inc, Daegu, South Korea). Various CBTs of 0.5, 1.2, 2.0, and 3.0 mm were incorporated—having been chosen to represent the available data for human maxillary and mandibular bone[12,13]—with the remaining part being cancellous bone.

A nonlinear FE analysis was used. The first step of the analysis commenced by meshing all models as is shown in Figure 1. For more accurate element analysis, a mesh window option was utilized by the software for both cortical and cancellous bone models to produce finer elements of an area of 0.5 mm representing the actual OMI/cortical and cancellous bone interface.

Various force magnitudes (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 N) were horizontally and separately applied to the OMI head as inserted into the different bone assemblies with different CBTs to simulate typical orthodontic forces loaded onto microimplants (Figure 1). For this, a total of 32 simulations were prepared for processing. Each part of the assembly was given appropriate material properties as adopted in previous studies[14,15] (Table 1). Homogeneity, isotropy, and linear elasticity were assumed for both the OMI and bone, and a friction coefficient of 0.3[16,17] between the microimplant and both cortical and cancellous parts was assigned, while contact between the latter two parts was assigned as an intimate with no friction.

To determine the values of compressive radial stresses developed for each CBT/force assembly used, five reference points (P1–P5) at 0.1-mm intervals tracked along the cortical bone surface in the force direction were registered (Figure 2). The maximum compressive stress (peak stress [PS]) developed at a point of intimate contact of the OMI and cortical bone (Point A) was then calculated using the five points; this stress level was considered a reference to compare with the reported maximum compressive stress of around 54.8 MPa, which is equivalent to −4000 micro strain, the point at which pathological cortical bone resorption might occur.[11,18–20] For the

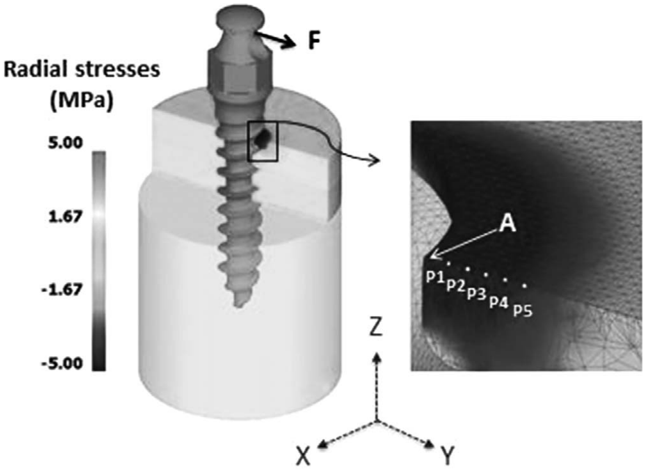

Figure 2. Results obtained from FE simulation process, with a magnified cross-section of the cortical bone area of concern with Point A and the reference points (P1–P5) shown.

sake of accuracy and predictability and to avoid singularity problems that might occur when analyzing stresses near sharp corners, the PSs were estimated by quadratic regression analysis using the statistical software SPSS version 21 (IBM Corp, Armonk, NY).

RESULTS

For each CBT tested, the developing compressive radial stresses were found to be directly related to the forces applied. As the force magnitude increased, the compressive stress also increased (Figure 3). On the other hand, an increase in CBT was shown to be accompanied by more conservative tolerance of the forces applied. As is shown in Figure 4, for each force applied, the increase in CBT led to more reduction of the stresses.

When the threshold stress was compared with the resulting PSs for each CBT/force assembly tested, the maximum forces that could be applied relative to each CBT were then shown (Figure 5). The direct relation between force and PSs shown on the chart permitted continuing the plotted lines to determine the maximum force magnitudes that could be loaded onto CBTs of 1.2, 2.0, and 3.0 mm. For CBTs of 0.5, 1.2, 2.0, and

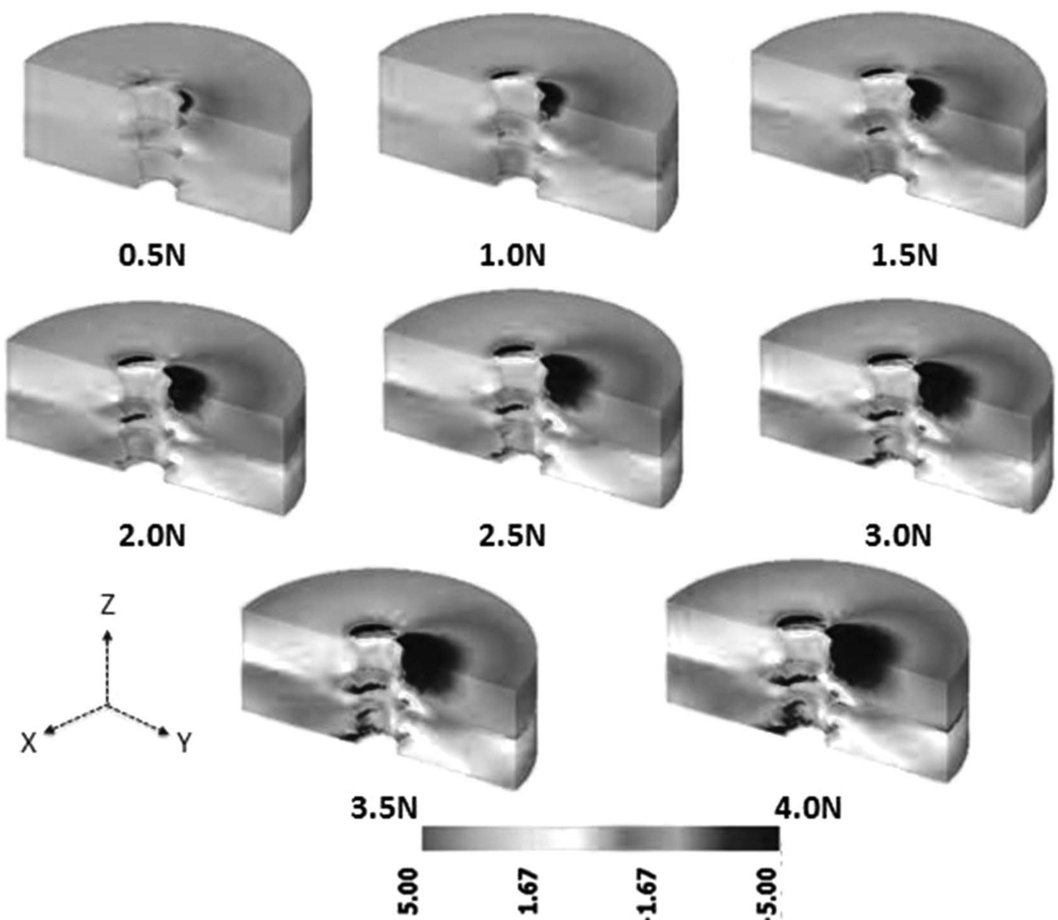

Figure 3. Compressive radial stresses developed as a result of application of different force magnitudes on the same CBT (2 mm is shown here).

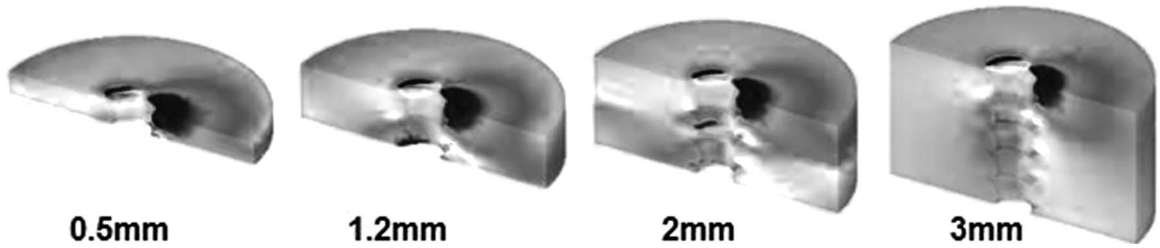

Figure 4. Compressive radial stresses developed as a result of application of a certain force (2N is shown here) to the different CBTs used in the study.

3.0 mm, the maximum force magnitudes that could be safely applied were 3.75, 4.1, 4.3, and 4.45 N, respectively.

DISCUSSION

The impact of applying orthodontic forces on microimplants should be comprehensibly studied in two ways; those effects developed at the area of insertion, which is composed of bone tissue, and those effects on the microimplant itself. As most of the OMIs available nowadays are made of titanium alloy (Ti-6Al-4V), compared with pure titanium, problems of deformation or fracture due to force application are almost negligible. Therefore, greater concern has arisen for the irreversible changes the bone might develop as a consequence. In this study, a standardized microimplant model (identical size and design) was inserted into different bone areas (different CBT and same bone density) and then different force magnitudes were applied to simulate the usual clinically loaded orthodontic forces.

Inasmuch as cortical bone has been previously reported to be a key determinant of total OMI success and the main bearer of orthodontic stresses, CBT was taken as a reference to compare the impact of loading the various force magnitudes.[21,22] For this reason, and to simplify analysis, only the stresses developed in cortical bone—rather than those developed in cancellous bone—were analyzed in this study.

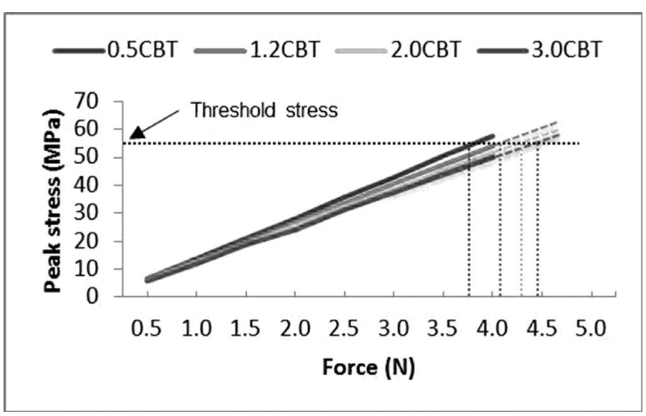

Figure 5. Peak stresses developed at points A relative to the different CBTs tested in the study with the threshold stress pointed out.

The development of a stress field incorporating the alveolar bone around the microimplant is reportedly correlated with OMI failure.[23,24] Excessive force application may result in unwanted compressive stresses that contribute to the development of microdamage of the cortical bone areas contacting the microimplant. Microdamage is a permanent deformation of the microstructure of loaded cortical bone in the form of fatigue and creep, manifesting histologically as microcracks around the implants and leading to osteolysis around the implant and loss of stability.[25,26]

The results of this study showed that the values of the compressive stresses were directly related to the magnitude of the forces applied, reflecting the elasticity of bone. Also, as CBT increases, peak stresses decrease. This might be clarified by the wider distribution of load into the cortical bone area without concentrating the developed stress into a small area like that in thinner bone. These results coincide well with those of other researches.[5,27,28]

The threshold for triggering pathologic resorption of human cortical bone was set in this study at −4,000 microstrains, which is equivalent to a threshold compressive stress of 54.8 MPa. According to Frost's mechanostat,[20] the normal physiologic range of bone loading is around 200 to 2500 microstrains, and the ultimate strength of bone is around 25,000 microstrains. When the peak strain exceeds 2500 microstrains, subperiosteal hypertrophy builds bone mass to reduce surface strain. If bone is repetitively loaded at around 4000 microstrains, fatigue damage accumulates more rapidly than it can be repaired, and the bone is at risk for stress fracture. Accordingly, repetitive loading of large orthodontic forces on an OMI beyond an optimum level—that might result in stress level exceeding the above threshold—may compromise the integrity of the surrounding bone and affect microimplant stability.

For each CBT force considered in this study, a unique and maximum force magnitude was shown to keep the compressive stresses within the adaptive window of cortical bone. For CBTs of 0.5–3.0 mm, 3.75–4.45 N forces were found to be the maximum levels to consider, which is consistent with the load magnitudes recommended by Park.[29] This level of forces reflects the capacity of bone to withstand the stresses encountered, based on the assumption that the bone is free of any prestresses. In other words, for the purpose of immediate orthodontic loading and, as bone is already stressed by the insertion procedure, the resultant force magnitudes mentioned above are not suitable.

Calculation of the remnant stresses of insertion is complex, and the expected bone remodeling might alter the bone's elastic properties. Conversely, as the duration of the human bone remodeling cycle is about 4 months,[30] and as osseointegration is occurring throughout this period of the microimplant's life, absorption of these remnant stresses, bone adaptation, and formation of healthy surrounding cortical bone is also taking place. These processes give clinicians the ability to increase forces to the levels found in this study.

Another entity to explore is that, in this study, the PSs represented only a small area of the compression side, while the remaining areas around the microimplant do not have the same level of stress. However, it should be stated that OMIs, compared with conventional dental implants, are usually subject to unidirectional lateral loadings and that concentrating compressive stresses in a small area of the cortical bone on the compression side could negatively affect its structural integrity. The presence of even small areas at high risk of developing bone pathology should be considered as frustrating microimplant prognosis.

It is safe to say that the results of this study were based on an environment wherein the only significant factor is the force magnitude and the only variant to compare the impact of force magnitudes is the CBT. However, clinically this is not the case. Other factors investigated by researchers related to bone density, microimplant size and design, surgical techniques used, proximity to root surface, bite forces, soft tissue condition, force direction, and moments generated by forces also share in microimplant success.[31,32]

Such results based on a quantitative FE analysis need to be validated by histological and clinical studies. Accordingly, we recommend starting OMI loading with a minimal force of 0.5–1.0 N and after 3–4 months, as needed, increasing this level up to around 3.5–4.5 N, as found in this study, considering cortical bone thickness.

CONCLUSIONS

Within the limitations of this study:

- The optimal force magnitude to be loaded onto an orthodontic microimplant to fulfill biomechanical demands and without diminishing microimplant stability should not exceed about 3.75–4.5 N, considering cortical bone thickness. Beyond this magnitude, compressive stresses exceeding the normal capacity of bone to withstand might develop which could affect the integrity of surrounding bone and place the microimplant under risk of failure.

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