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Influence of insertion depth on stress distribution in orthodontic miniscrew and the surrounding bone by finite element analysis

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We aimed to elucidate stress distribution in miniscrews and the surrounding bone when miniscrews inserted at different depths were implanted vertically or obliquely. The distributions of the equivalent stress on the screw surface and the minimum principal stress in the surrounding bone were calculated using finite element models. When the miniscrews were inserted vertically and obliquely, screw head displacement, greatest equivalent stress on the miniscrew surface, and absolute value of minimum principal stresses in the surrounding bone decreased with increasing insertion depth. Stresses in the obliquely inserted miniscrew with upward traction were smaller than in other insertion conditions, irrespective of insertion depth. With the application of orthodontic force, stress distribution around the miniscrew and surrounding bone is closely related to the insertion depth and insertion angle, which mutually affect each other. In particular, the obliquely inserted miniscrew with upward traction might be the most secure against screw failure and fracture.

Keywords: Finite element analysis, Orthodontic miniscrew, Insertion depth, Insertion angle

INTRODUCTION

Twenty-five years ago, the use of miniscrews caused a paradigm shift in modern orthodontics. Since then, the miniscrews significantly expanded the limits in clinical orthodontics. In spite of their small diameter and short length, orthodontic miniscrews are very effective and useful tools in current orthodontic treatment[1,2]. Even without patients' cooperation, miniscrews provide absolute anchorages for various tooth movements and enable us to move the tooth in directions that were impossible with conventional orthodontic techniques[1,2].

To date, various types of miniscrews were developed and distributed worldwide; their length ranges from 5 mm to 12 mm, and their diameter ranges from 1.3 mm to 2.0 mm. The selection and use of miniscrews should be based on each case according to the aim, insertion method, and location[3].

When placing a screw at the interradicular area of the buccal alveolar bone, short screws have the advantage of avoiding root proximity[4,5]. For screws placed at the palatal site, short screws are preferred to avoid perforation of the maxillary sinus and nasal cavity[6]. Kang *et al.*[7] showed that the average thickness of the palatal bone at the premolar to molar regions is <5 mm. Conversely, when placing screws in the buccal alveolar bone of the mandibular molar site, where the gingiva is generally thicker, longer screws are preferred to avoid burying the screw head into the gingival mucosa[8,9].

For orthodontic tooth movement, the amount of maximal force is <200 g. To use a miniscrew as an orthodontic anchorage during tooth movement, >5 mm of screw body must be inserted into the bone. Therefore, the proper length of the screw is 5 mm (inserted into the bone)+the thickness of the gingival mucosa. However, because a large difference in gingival thickness exists between individuals, the length of insertion into bone may vary[10].

Conversely, using three-dimensional (3-D) finite element (FE) analysis, a few studies have investigated the stress distribution in miniscrews and surrounding tissues in application of orthodontic force when the miniscrews were inserted to a specific depth[11-16]. In an investigating the role of implanted depth on the biomechanics of an orthodontic miniscrew, Liu *et al.*[11] used FE models with different insertion depths to demonstrate that the bone stress and screw displacement decreased with decreasing exposed length when the miniscrews were implanted vertically. However, only limited information is available on the influence of miniscrew insertion depth and direction on stress distribution and screw stability. Thus, we hypothesized that the stress distribution in miniscrews and the surrounding bone is affected by the insertion

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depth and direction of miniscrews, which interact with each other. The aim of this study was to assess the stress distribution in miniscrews and the surrounding bone when miniscrews inserted at different depths were implanted vertically or obliquely using a 3D FE model.

MATERIALS AND METHODS

This study was approved by the Clinical Ethics Committee of Tokushima University Hospital (Approval No. 2455). For this study, we used titanium miniscrews (Type-TK D1.6×L7, B-max Screw, BIODENT, Tokyo, Japan). The miniscrews exhibited a shaft length of 5.2 mm, pitch of 0.5 mm, depth of 0.2 mm, and taper of 2.0°. The screw thread was created by setting the proximal half angle at 35° and the distal half angle at 10°. Based on the computer-aided design (CAD) data provided from BIODENT, the 3-D FE models of the miniscrews were constructed.

The surrounding bone was modeled as cylindrical structure. It composed of cortical bone with 2.0 mm in thick and cancellous bone with 5.0 mm in thick (Fig. 1). The miniscrew models were inserted into the bone model at four different depths (4.1 mm, 4.6 mm, 5.1 mm, and 5.6 mm). Furthermore, these miniscrews were inserted in two different directions related to the cortical bone surface. The direction perpendicular to the cortical bone surface was defined an angle of 0°. One additional model of each screw was created to represent screw orientations of 30° (Fig. 1). A total of 10 FEMs were meshed by delta cone tetrahedral solid elements using HyperWorks (Altair Engineering, Troy, MI, USA).

All solid elements were characterized to be isotropic, homogeneous, and linear elastic. Table 1 shows the mechanical properties of cortical and cancellous bones and the miniscrews. The bone model was restrained for all degrees of freedom at the bottom and the peripheral edge to avoid sliding movements of the entire model. The interfaces between the cortical and cancellous bone were all assumed to be bonded. Contact was modeled using nonfrictional contact elements between the screw and surrounding tissue. This enabled the two contacting surfaces to move independently.

For the loading condition, the magnitude of traction force was defined 2 N, which is almost equal to application force to a miniscrew in clinic. For each model, the traction force was loaded to the center of the screw head hole in four different directions (upward, downward, right-side, and left-side; Fig. 1). The equivalent stress and minimum principal stress were calculated for all nodes of the screw and bone, respectively. The stress distribution on the screw surface and in the surrounding bone as well as the displacement of the screw head point on which the traction force was applied, were assessed using the FE analysis program Nastran (Autodesk Nastran version 2018, Autodesk, San Rafael, CA, USA).

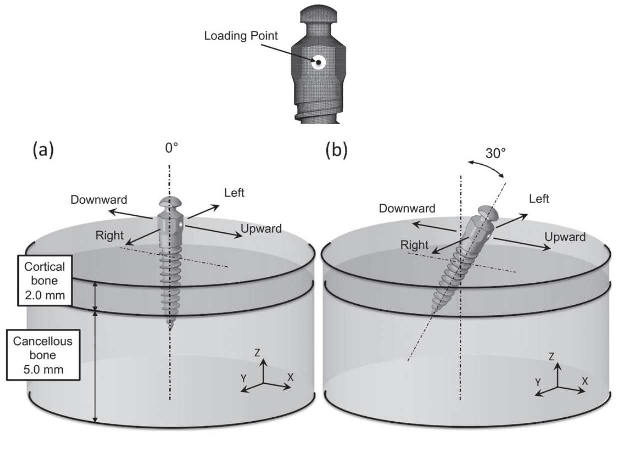

Fig. 1 Schematic illustration of miniscrew used for FE analysis.
The direction perpendicular to the cortical bone surface was defined as an angle of 0°. Screws were inserted with the direction of (a) 0° and (b) 30°.

RESULTS

Displacement of screw head

When screws were inserted vertically, the displacement of the screw head on which the load was applied was almost the same regardless of force application direction. When the insertion depth was 4.1 mm, the displacement of the screw head was 0.0131 mm on average. When the insertion depth increased, the displacement of the screw head decreased by about 71% (Fig. 2). Meanwhile, when the miniscrews were inserted obliquely, the displacement of the screw head was the smallest at the upward force application, irrespective of the insertion depth, whereas the displacement was greatest at the downward force application. Also, the displacement decreased as the insertion depth increased.

Stress distribution on the miniscrew surface

Figure 3 shows the distribution of equivalent stress on the screw surface. Figure 4 shows the projection

Table 1 Material properties of constituent materials[24]

	Elastic modulus E (GPa)	Poisson ratio ν	Yield Strength[25] (MPa)
Miniscrew (Ti6Al4V)	114.0	0.34	880
Cortical bone	14.7	0.30	—
Cancellous bone	1.5	0.30	—

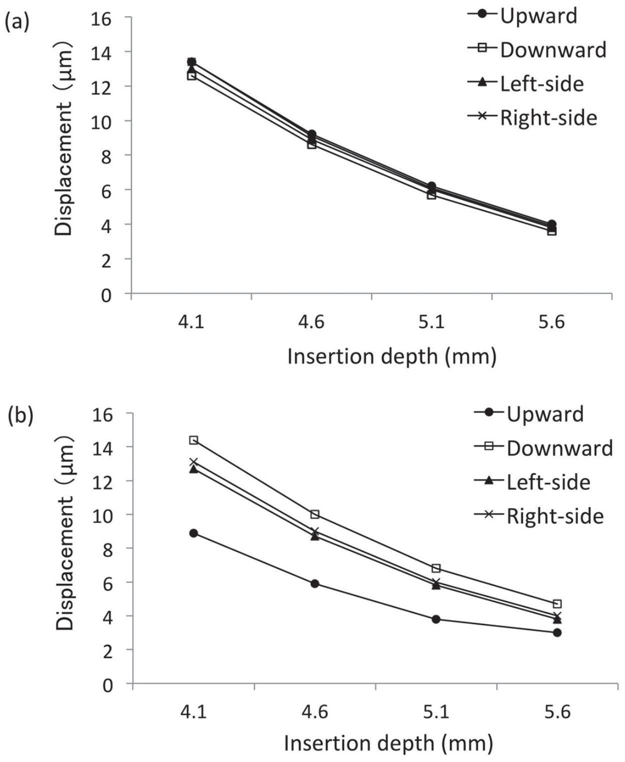

Fig. 2 Displacement of screw head.
(a) Vertical insertion (0°). (b) Oblique insertion (30°).

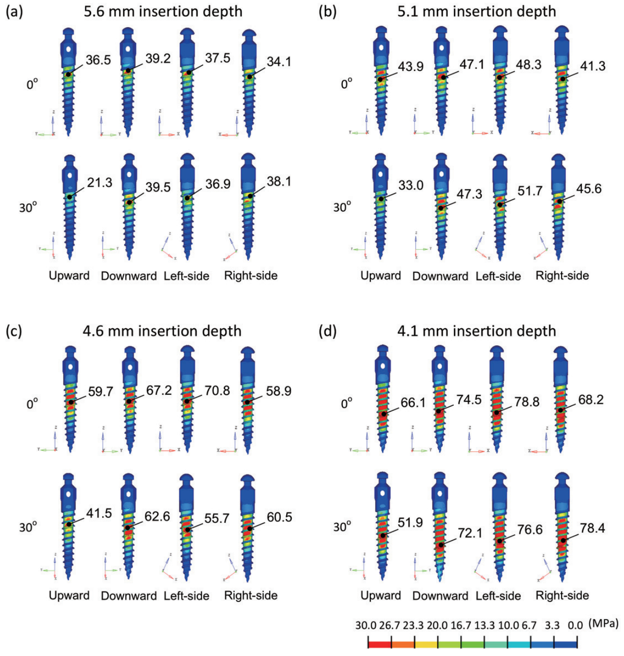

Fig. 3 Distribution of equivalent stress on the surface of miniscrews on the loaded side when both miniscrews were inserted vertically (0°) and obliquely (30°). Insertion depth of (a) 5.6 mm, (b) 5.1 mm, (c) 4.6 mm, and (d) 4.1 mm.

of the equivalent stresses to the screw surface in the axial direction plane on which the greatest equivalent stresses were located. When the screws were inserted vertically, the greatest equivalent stress induced onto the screw surface decreased with an increment of the insertion depth. The location of the greatest equivalent stress was matched to the contact point of the screw to the cortical bone regardless of the insertion depth and the force application direction. When the insertion depth decreased, the equivalent stress was spread over the wider area of the miniscrew.

When the screws were inserted obliquely, the greatest equivalent stress also decreased with an increment of the insertion depth. The decreased rate of greatest equivalent stress was approximate 50%. With upward traction, the greatest equivalent stress was the smallest irrespective of the insertion depth. The equivalent stress was distributed to the wider area of the screw surface at 4.1 mm insertion depth. At the downward, right-side and left-side traction, the greatest equivalent stresses were located at the contact point to the cortical bone layer, whereas at the upward traction, the location of the greatest equivalent stress was displaced from the cortical bone layer to the upper site.

By comparing the equivalent stresses between the screws inserted vertically and obliquely, the greatest equivalent stress values were almost the same, except at the upward traction. At the upward traction, the greatest equivalent stress was greater when the screw was inserted vertically than when the screw was inserted obliquely. When the screw was inserted obliquely and the force was applied upward, the value of the greatest equivalent stress was about 60–80% of that when the screw was inserted vertically.

Stress distribution in the cortical bone

When the miniscrew was inserted vertically, the minimum principal stresses were concentrated on the surface of the cortical bone, irrespective of the force application direction and the insertion depth. With an increment of the insertion depth, the increase of the minimum principal stresses occurred independently of the force application direction, indicating a decrease in the absolute values of the minimum principal stresses. The absolute values of the minimum principal stresses were reduced to 40–70% when the insertion depth was increased from 4.1 mm to 5.6 mm (Fig. 5).

When the miniscrew was inserted obliquely, the minimum principal stresses were also located at the surface of the cortical bone regardless of the force application direction. At the upward traction, the smallest values of the minimum principal stresses were −17.3 MPa, −13.6 MPa, −13.6 MPa, and −7.8 MPa at 4.1 mm, 4.6 mm, 5.1 mm, and 5.6 mm of the insertion depth, respectively. These values were larger than those at the downward, left-side and right-side traction. When the insertion depth was increased from 4.1 mm to 5.6 mm, the reduction rate of the absolute values of the minimum

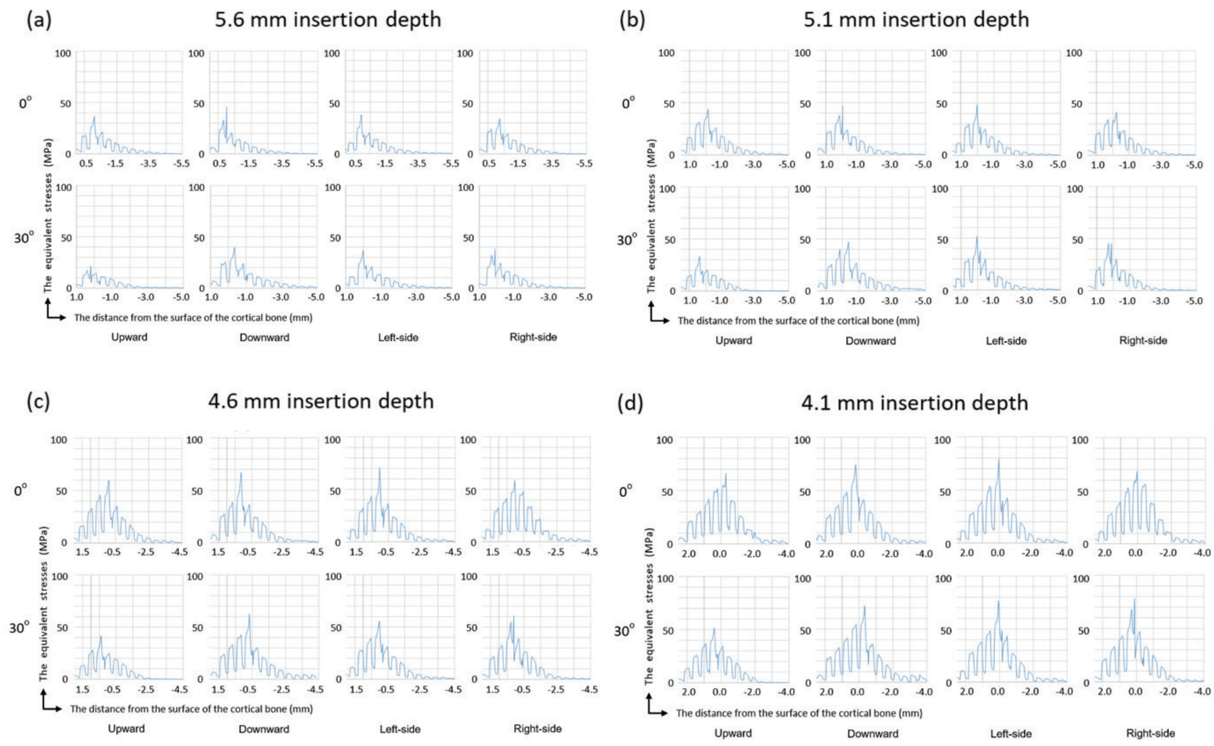

Fig. 4 The projection of the equivalent stresses to the screw surface in the axial direction plane on which the greatest equivalent stresses were present when both miniscrews were inserted vertically (0°) and obliquely (30°).
The horizontal axis shows the surface of the cortical bone as 0 point and represents the distance from it. The screw head was set as the positive direction. Insertion depth of (a) 5.6 mm, (b) 5.1 mm, (c) 4.6 mm, and (d) 4.1 mm.

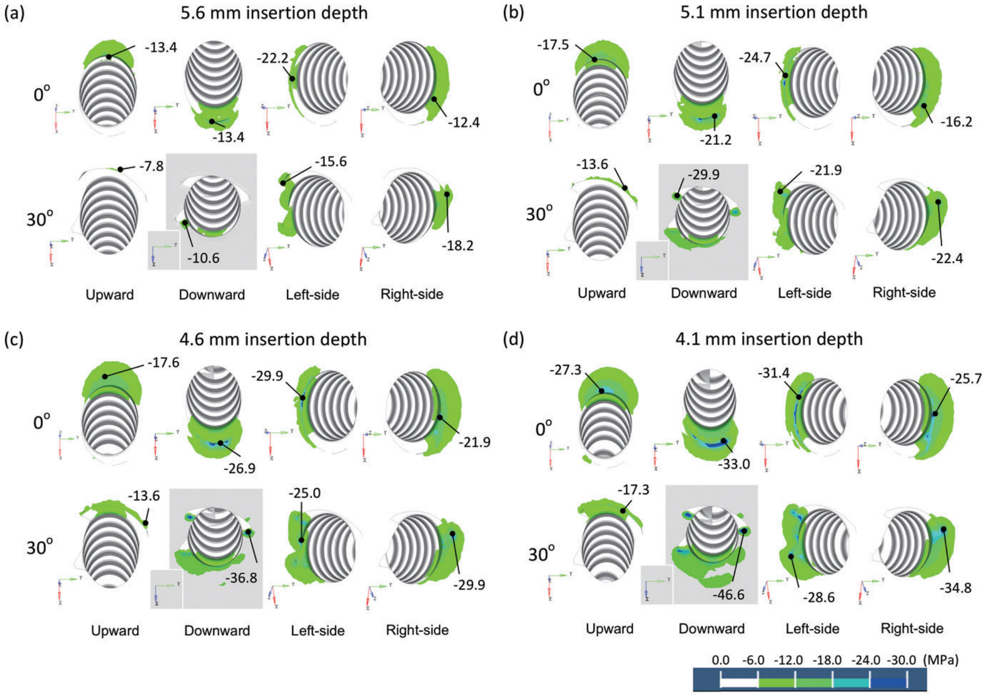

Fig. 5 Distribution of minimum principal stress on the surface of cortical bone under orthodontic force application when both miniscrews were inserted vertically (0°) and obliquely (30°).
Insertion depth of (a) 5.6 mm, (b) 5.1 mm, (c) 4.6 mm, and (d) 4.1 mm.

principal stresses was 44–55%.

When the screw was inserted obliquely and the force was applied upward, the absolute values of the smallest minimum principal stresses were 58–78% of those when the screw was inserted vertically.

DISCUSSION

In clinical orthodontics, miniscrews are commonly used to obtain stable anchorage for various tooth movements, including intrusion, retraction, and protraction. However, the use of miniscrews exhibits some associated risks and complications[17)]. Many factors were explored and are being suspected of being associated with screw failure. In terms of host factors, age, oral hygiene control, implant site, cortical bone thickness, and bone density were reported[2,18)]. In terms of technical factors, screw structure such as diameter, length, and taper, screw thread shape, insertion method, insertion torque, insertion angle, loading amount, loading direction, screw-root proximity, and microfracture of alveolar bone were indicated[4,5)]. In addition, another important technical factor for screw failure is the insertion depth of miniscrews into the alveolar bone. Several studies investigated the importance of miniscrew stability[4,19)]. In their clinical study, Fritz *et al.*[20)] demonstrated that miniscrews with 4-mm length provide proper stability compared to 6- and 8-mm miniscrews. Cheng *et al.*[21)] could not recognize implant length to exhibit a significant correlation with implant failure clinically, although implant length was determined only by transmucosal depth rather than by the depth of bone available for anchorage. Duaibis *et al.*[22)] reported that intrabony miniscrew length has no effects on stresses in cortical bone, but increasing the extrabony head length of the miniscrew increases the stresses in cortical bone and may therefore compromise the stability. Liu *et al.*[11)] noted that the ratio between the inserted and external parts of the miniscrew was one of the most important factors affecting stresses in cortical bone. This may provide more insight into optimal screw placement, leading to sufficient stability of miniscrews and more promising orthodontic treatment.

When traction force is applied to the miniscrew, the surrounding bone is also loaded, resulting damage and deformation of the alveolar bone from excessive mechanical stress. When stress is applied to bone, microfracture occurs. That microfracture is described as "strain", and 0.1% deformation by total volume is defined as 1,000 με. Based on the mechanostat theory, Frost[23)] reported that the threshold value for overload-induced bone resorption in a cortical bone is 3,000 με. This strain is equivalent to a stress of 44.1 MPa (if the bone is assumed to be elastic with a modulus of 14,700 MPa)[24)]. A 0.4-mm thick alveolar mucosa was set as a model on the surface of cortical bone, but the minimum principal stresses were so small that they were omitted from the analysis. Our results showed that when the screws were implanted vertically with >4.1 mm insertion depth, the minimum principal stresses of the surrounding bone were <44.1 MPa regardless of the direction of traction force. This indicates that microfractures of the surrounding bone rarely occur if the screws are inserted vertically into alveolar bone at a depth of >4.1 mm. Conversely, when the screws are implanted obliquely, the screw head displacement and the resultant minimum principal stresses in the surrounding bone depend on the traction direction. At the upward traction, the amount of the screw head displacement and the absolute values of minimum principal stresses in the surrounding bone were decreased markedly as compared with other tractions. However, at the downward traction, the absolute values of minimum principal stresses exceeded 44.1 MPa at 4.1 mm insertion depth. This implies that oblique screw placement with >4.6 mm insertion depth is recommended if the orthodontic force is applied downward. However, the downward traction to obliquely implanted miniscrews is extremely rare in clinical situations.

In this study, we also investigated the effect of the ratio between the inserted and external parts of the miniscrew. The external screw lengths (total screw length minus inserted depth) were increased from 4.0 mm to 5.5 mm as the insertion depth was decreased from 5.6 mm to 4.1 mm. The ratios between the inserted and external parts of the miniscrew were 1:0.7, 1:0.9, 1:1.1, and 1:1.3 at 5.6 mm, 5.1 mm, 4.6 mm, and 4.1 mm of the insertion depth, respectively. When screws were inserted vertically, the greatest equivalent stress in cortical bone increased as the external screw length increased, regardless of force application direction. Even at a ratio of 1:1.3, the greatest equivalent stress was well below 44.1 MPa. The same tendency was observed when the miniscrew was inserted obliquely; however, the greatest equivalent stress in cortical bone was obviously less with upward traction than with downward traction. Therefore, when the traction force was applied upward, the greatest equivalent stress in the obliquely inserted screw at the ratio of 1:1.3 was almost equal to that in the vertically inserted screw at the ratio of 1:0.9. Notably, the greatest equivalent stress was reduced and the stability of miniscrews was improved by an oblique screw insertion with upward traction, even with increased length of the miniscrew's external parts. To the best of our knowledge, this is the first study to examine the effect of the ratio between the inserted and external parts of miniscrews implanted vertically or obliquely.

Our results showed that the greatest equivalent stress of the miniscrew was <78.8 MPa, even if the insertion depth was 4.1 mm. Especially when the screw was placed obliquely and the traction force was applied upward, the value of the greatest equivalent stress was the smallest. The yield stress of the titanium alloy (Ti6Al4V) was reported as 880 MPa[25)], and the fracture point of 1.6-mm-diameter miniscrews was reported to be 29.78±4.8 Ncm[26)]. Thus, a miniscrew insertion with >4.1 mm insertion depth does not appear to increase the risk of screw fracture. Kuroda *et al.*[12)] demonstrated that the equivalent stress in the screw was concentrated on the screw neck. The present study showed no or less stress concentration at the neck of the miniscrew, although equivalent stresses were spread over the wider area on the screw surface. This may be due to the difference in the screw shape. Conversely, jiggling insertion and removal of miniscrews are likely to induce excessive torsion at the screw neck, subjecting to screw loosing and fracture. Thus, close attention should be paid to ward off screw fracture during screw insertion and removal, even when the miniscrews are inserted obliquely.

A previous study suggested that tapered screws might be most stable with upward traction12). In the present study, similar results were observed for oblique screw implantation with any insertion depth. These results could possibly be explained by the reduced moment force with upward traction as compared with other tractions. Moreover, the location of the greatest equivalent stress was displaced at the upward traction to the slightly upper site from the cortical bone layer (Fig. 4). Therefore, the absolute values of the minimum principal stresses in the surrounding bone were decreased as compared with other tractions. Taking these findings into consideration, we concluded that when the miniscrew was inserted obliquely with at least 4.1 mm insertion depth and the force was applied upward, the miniscrew can achieve adequate stability as an orthodontic anchorage during tooth movement. Oblique implantation in clinical settings can be suitably used as the anchorage source for intruding anterior teeth in deep bite cases, intruding molars in anterior open bite cases, and molar distalization in crowding cases27,28).

CONCLUSIONS

1. Stress distribution on the surfaces of miniscrew and the surrounding bone in orthodontic force application is closely related to the insertion depth and insertion angle.
2. The displacement of the screw head, the greatest equivalent stress on the miniscrew surface, and the absolute values of minimum principal stresses in the surrounding bone were decreased with increasing the insertion depth, irrespective of the angle of screw insertion.
3. When the miniscrew was implanted vertically with >4.1 mm insertion depth, microfractures of the surrounding bone are considered unlikely to occur, regardless of the direction of force application.
4. Obliquely inserted miniscrews with an upward traction are the most secure against screw failure and fracture.

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