Original Article

Mechanical Characteristics of Various Orthodontic Mini-screws in Relation to Artificial Cortical Bone Thickness

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ABSTRACT

Objective: To evaluate the effect of cortical bone thickness on the maximum insertion and removal torque of different types of self-drilling mini-screws and to determine if torque depends on the screw design.

Materials and Methods: Three different types of self-drilling mini-screws (cylindrical type [Cl], taper type [Ta], taper type [Tb]) were inserted with the use of a driving torque tester at a constant speed of 3 rotations per minute. Experimental bone blocks with different cortical bone thicknesses were used as specimens.

Results: Differences in the cortical bone thickness had little effect on the maximum insertion and removal torque in Cl. However, with Ta and Tb, the maximum insertion torque increased as the cortical bone thickness increased. The maximum insertion torque of Tb was highest in all situations, followed by Ta and Tb, in that order. Cl showed less torque loss in all cortical bone thicknesses and a longer removal time compared to Ta or Tb. There were significant relationships between cortical bone thickness, maximum insertion and removal torque, and implantation time in each type of self-drilling mini-screw.

Conclusion: Since different screw designs showed different insertion torques with increases in cortical bone thickness, the suitable screw design should be selected according to the cortical thickness at the implant site.

KEY WORDS: Orthodontic mini-screw; Insertion torque; Removal torque

INTRODUCTION

Recently, efforts to find a new type of anchorage other than the classic types of anchorage have been developed. There have been many studies about the ability of osseointegrated implants, onplants, zygomatic arch wiring, and mini-plates to obtain absolute anchorage without the need of patient cooperation.[1–4] Later, many studies and successful clinical cases were reported describing the possibility of using mini-screws as orthodontic anchorage.[5–9]

The success rate of mini-screws has been reported by Costa et al,[9] who noted that 2 cases of 16 failed. Tseng et al[10] reported a success rate of 91.1%, and Park et al[11] reported a relatively high success rate of 93.3%. It was reported that the drill-free method showed better results and success rates, bone implant contact ratio, and bone density than the drilling method did.[12] It was also reported that gender did not have a significant effect on the stability of mini-screws, but the jaw of placement showed significant difference in terms of the failure rate.[13] Likewise, many studies regarding the stability of mini-screws have focused on patient factors or the insertion method. A more fundamental factor of failure in mini-screws is thought to be the displacement caused by the problem of the interface between the mini-screw and bone tissue. This is also related to the quality and quantity of bone at the implantation site, screw design including diameter, screw length, and pitch design and screw material.[14,15]

Finite element analysis studies have suggested that the diameter rather than length plays a greater role in their retention as demonstrated in studies about stress distribution in reference to the length and diameter of

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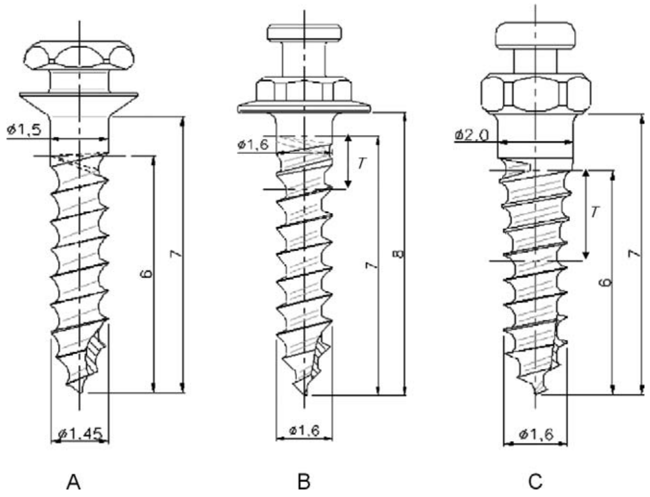

Figure 1. Schematic diagram for each type of mini-screws used in this study. T indicates portion of taper part (unit = mm).

mini-screws and cortical bone thickness.[16,17] Studies of stress distribution inside the cortical bone have reported that the length of a mini-screw does not influence the maximum stress and stress distribution and that the cortical bone thickness does not influence the maximum stress.[18] However, since the mini-screw used in both studies did not have any tapered structure at the contact site with cortical bone near the top of screw, the influence of screw design on cortical bone thickness was ignored.

When a mechanical evaluation of the stability of screw-shaped implantation including mini-screws is made, insertion and removal torques and pull-out strengths are generally measured.[19–23] A previous review of mechanical studies mentioned that the bone density at the insertion site is a factor influencing stability.[20] Thus, to control the bone density factor, artificial bone with a uniform density value was used.[24] In addition, in former studies, the main method used to measure torque was manual operation of a manometer or torque screwdriver. As a result, it was difficult to maintain rotational speed or uniform vertical force and almost impossible to measure torque serially. Koistinen[24] reported good reproducibility of the experiment using a driving torque tester.

Table 2. Mechanical Properties of Experimental Bone Used in This Study

Alternative Test Medium	Density, g/cc	Compressive, MPa		Tensile, MPa	
		Strength	Modulus	Strength	Modulus
Cortical bone	1.7	120	7600	90	12,400
Cancellous bone	0.64	37	943	16	1190

There were few studies concerning the mechanical characteristics of mini-screw or retention factors, although applications of the mini-screw as an orthodontic anchorage have became more common in recent orthodontic treatment. The purpose of this study is to examine the mechanical characteristics of the mini-screw through serial torque measurements during the insertion and removal of three different types of drill-free–type orthodontic mini-screws into and from artificial bone samples with different cortical bone thicknesses using a driving torque tester.

MATERIALS AND METHODS

Drill-free–type orthodontic mini-screws of different manufacturers were chosen based on each having a characteristic structure with a similar outer diameter and a screw thread length. They were classified according to the morphologic characteristics of the screw by surveyed principal measurements of each mini-screw using an instrumental microscope (MF-A1010H; Mitutoyo Corp, Tokyo, Japan; Figure 1, Table 1).

In this study, an experimental artificial bone block (Sawbones; Pacific Research Laboratories Inc, Vashon Island, WA, USA) was used. E-glass–filled epoxy sheets and solid rigid polyurethane foam were used as alternate experimental materials of cortical and cancellous bone, respectively (Table 2). The E-glass–filled epoxy sheets were cut into 1-, 1.5-, and 2-mm sizes using a milling machine (NSM-A; Nam Sun Machine Tools co Ltd, Seoul, Korea) and attached to solid rigid polyurethane foam using acrylate bond (Automix; 3M, St Paul, MN, USA). The blocks were 110 mm long, 10 mm wide, and 10 mm high.

Table 1. Principal Properties and Dimensions of the Mini-screws Used in This Study

	Type A	Type B	Type C
Screw design	Pure cylindrical	Combined cylindrical part + taper part	Combined cylindrical part + taper part
Corporation	Biomaterials Korea	Jeil Medical	Ortholution
Body length, mm	7.0	8.0	7.0
Thread length, mm	6.0	7.0	6.0
Thread diameter, mm	1.5	1.6[a]	1.6 (2.0)
Taper length, mm	—	1.5	2.5
Chemical composition	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V

[a] X@XType B screw has a constant outer thread diameter as 1.6 mm with an increasing inner core diameter in a taper part.

Figure 2. Photo image of torque tester (Biomaterials Korea Inc, Seoul, Korea).

Driving Torque Test

Using a driving torque tester (Biomaterials Korea Inc, Seoul, Korea; Figure 2) with a uniform speed of 3 rotations per minute (corresponding to the regulations of the American Society for Testing and Materials [ASTM] F543-02), the torque of insertion or removal of mini-screws versus time was shown on a graph. The values are shown in Table 3.

Insertion Torque Test

After the mini-screw tip was placed perpendicular to the artificial bone sample, it was inserted to the end of the screw thread by rotating the torque tester's rotational axis clockwise. During insertion, the torque was measured every 0.1 seconds using a computer program (QuickDataAcq; SDK Developer, London, UK; Figure 3). A 470-g weight was attached to the tester's rotational axis to provide enough perpendicular force for the mini-screw to perforate the cortical bone. A dial indicator depth gauge sensitive to 0.01 mm was used to accurately measure the insertion depth of the mini-screw. For each of the cortical bone samples, 10 mini-screws were inserted at intervals of 10 mm.

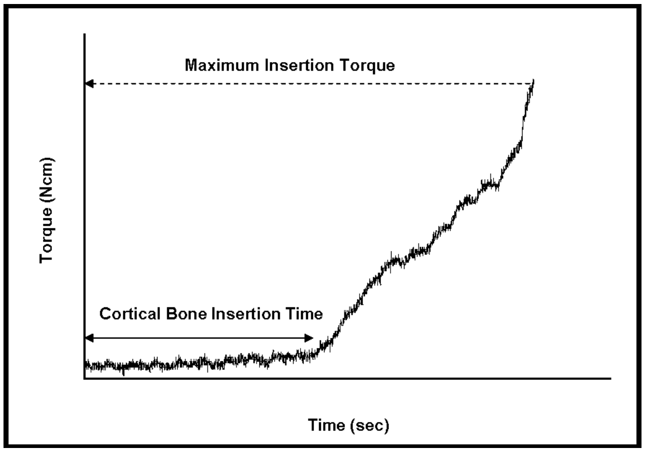

Figure 3. Time-insertion torque graph and the definitions of measurement values regarding the insertion torque test.

Removal Torque Test

By rotating the torque tester's rotational axis counterclockwise, torque was measured every 0.1 seconds while the mini-screw was being removed (Figure 4). Of the 10 inserted mini-screws for each subgroup, the removal torque was measured for 5.

Statistics

To observe the significance of the variables between each type and the thickness of the cortical bones, measurements were processed by a two-way analysis of variance using the SAS 8.2 (STAT User's Guide) program, and a ranking order was established using the Tukey Studentized range test.

RESULTS

Cortical Bone Insertion Time

The thicker the cortical bone, the larger the time needed for perforating the bone. In all the different thickness samples, the insertion time for type B was the shortest. Type C showed a large standard deviation in cortical bone samples 1.5 mm and 2 mm thick (Table 4).

Maximum Insertion Torque

Compared to the control group with only medullary bone, the maximum insertion torque (MIT) of type A increased when there was cortical bone, but no significant difference between the insertion torques was shown within the 1-mm to 2-mm range ($P > .05$). The MIT of types B and C increased significantly as the thickness of the cortical bone increased ($P < .05$). As the cortical bone thickness increased from 1 mm to 2 mm, insertion torque increased consistently for type C.

Table 3. Measurement Values and Definition Used in This Study

Measurements Values (Abbreviation)	Unit	Definition
Cortical bone insertion time (CBIT)	Seconds	The time taken for the tip of the mini-screw to perforate the cortical bone and start penetrating into the medullary bone (Figure 3)
Maximum insertion torque (MIT)	N cm	The maximum torque value during the beginning to the end of insertion of miniscrew (Figure 3)
Maximum removal torque (MRT)	N cm	The maximum torque value shown on a torque vs time graph when the mini-screw is removed during the driving torque test (Figure 4)
Torque loss (TL)	N cm	The difference between the maximum insertion torque and the maximum removal torque

In all thickness samples, MIT was in order of type C > type B > type A (Table 5).

Maximum Removal Torque

Compared to the control group with only medullary bone, the maximum removal torque (MRT) of type A increased when there was cortical bone, but no significant difference between the removal torques was shown within the 1-mm to 2-mm range ($P > .05$). The MRT of types B and C increased as the thickness of the cortical bone increased. In all three types, the MRT was lower than the MIT ($P < .05$; Table 6).

Torque Loss

Overall, the higher the MIT, the higher the MRT and torque loss, which is the difference between the two variables. Type A showed less torque loss than types B or C did (Table 7).

DISCUSSION

To observe the mechanical characteristics according to the thickness of the cortical bone, models made by three different companies with structurally different contact areas with cortical bone were selected. Screw design, which included diameter and length of screw or implant, and bone density of the insertion area are mentioned in many reports as factors that affect the stability of the screw.[20,25]

According to Ciarelli et al,[26] the strength and stiffness of the medullary bone are proportional to the bone density and orientation, and since these variables are not uniform within the medullary bone, there is a wide range of physical characteristics. Therefore, to control bone density as a variable, experimental artificial bone samples were used that have uniform density that does not change according to the insertion area and meet the ASTM regulations on mechanical studies of metal bone screws. Using artificial bone for mechanical experiments may show different results from that of human body, but having uniform cortical bone thickness and bone density and a fixed vertical load and direction is an advantage.

Type A, which is a purely cylindrical type, showed a relatively regular MIT value, except for the control group that consisted of only medullary bone. Therefore, it is considered that the part of the mini-screw that makes contact with cortical bone affects insertion torque value the most. As the screw part of type A is cylindrical except for the tip, the contact area with the cortical bone is not as wide as the tapered form screw. During insertion of the screw, the insertion path in cortical bone is formed so that when the diameter in the

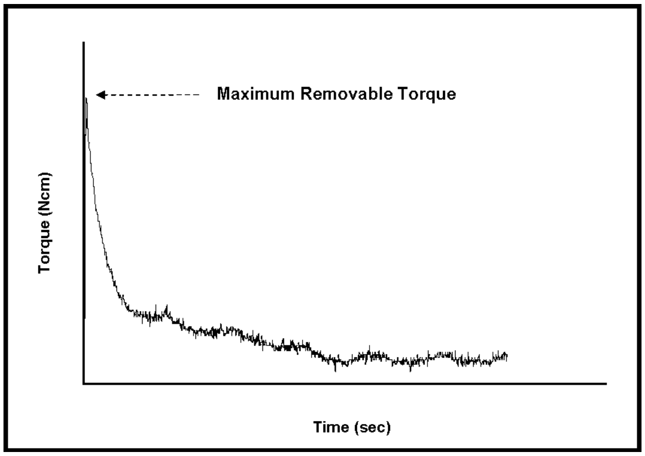

Figure 4. Time-removal torque graph and the definitions of measurement values regarding the removal torque test.

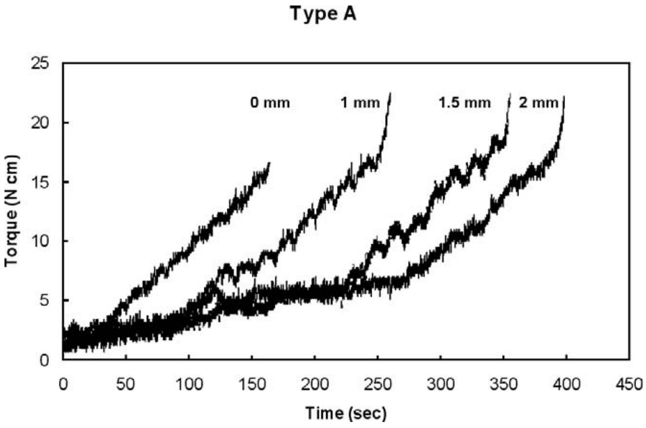

Figure 5. Superimposition of time-insertion torque graphs by cortical bone thickness in type A.

Table 4. Cortical Bone Insertion Time (s) According to Cortical Bone Thickness

	1 mm	1.5 mm	2 mm	Tukey's[a]
Type A	94 ± 0.55	144 ± 5.37	268 ± 14.21	1 < 1.5 < 2 mm
Type B	68 ± 2.05	103 ± 5.79	130 ± 6.04	1 < 1.5 < 2 mm
Type C	122 ± 1.48	132 ± 38.10	159 ± 39.97	1 < 1.5 < 2 mm
Tukey's	Type B < A < C	Type B < C = A	Type B < C < A	

[a] XStatistical significance is determined by Tukey's studentized range test ($P < .05$).

Table 5. Maximum Insertion Torque (N cm) According to Cortical Bone Thickness

	0 mm	1 mm	1.5 mm	2 mm	Tukey's[a]
Type A	16.73 ± 0.12	20.33 ± 0.10	20.33 ± 0.11	20.34 ± 0.13	0 < 1 = 1.5 = 2 mm
Type B	23.09 ± 0.50	30.31 ± 0.27	36.20 ± 0.91	38.01 ± 1.06	0 < 1 < 1.5 < 2 mm
Type C	23.91 ± 0.45	35.39 ± 0.40	37.89 ± 2.23	40.97 ± 3.86	0 < 1 < 1.5 < 2 mm
Tukey's	A < B < C	A < B < C	A < B < C	A < B < C	

[a] XStatistical significance is determined by Tukey's studentized range test ($P < .05$).

Table 6. Maximum Removal Torque (N cm) According to Cortical Bone Thickness

	0 mm	1 mm	1.5 mm	2 mm	Tukey's[a]
Type A	14.79 ± 0.94	18.23 ± 0.27	18.35 ± 0.19	18.46 ± 0.50	0 < 1 = 1.5 = 2 mm
Type B	21.68 ± 1.00	24.95 ± 0.46	27.83 ± 1.67	30.41 ± 0.38	0 < 1 < 1.5 < 2 mm
Type C	20.08 ± 1.10	27.99 ± 0.09	29.46 ± 1.65	31.93 ± 2.92	0 < 1 < 1.5 < 2 mm
Tukey's	A < C = B	A < B < C	A < B = C	A < B = C	

[a] XStatistical significance is determined by Tukey's studentized range test ($P < .05$).

Table 7. Torque Loss (N cm) According to Cortical Bone Thickness

	0 mm	1 mm	1.5 mm	2 mm	Tukey's[a]
Type A	1.58 ± 0.77	2.10 ± 0.23	1.98 ± 0.20	3.49 ± 0.52	0 < 1.5 = 1 < 2 mm
Type B	1.41 ± 0.73	5.36 ± 0.58	8.38 ± 1.80	8.60 ± 0.80	0 < 1 < 1.5 = 2 mm
Type C	3.83 ± 0.65	7.40 ± 0.33	9.43 ± 1.67	9.04 ± 1.74	0 < 1 < 2 = 1.5 mm
Tukey's	B = A < C	A < B < C	A < B = C	A < B = C	

[a] XStatistical significance is determined by Tukey's studentized range test ($P < .05$).

cortical bone reaches the maximum diameter of the screw, the increase in torque is mainly affected by the insertion depth on medullary bone. Hence, with the increase of cortical bone, the torque value remains constant, (Figure 5). With the increase of cortical bone thickness, only the time taken to perforate the cortical bone increased, and the increased rate of torque value against time was similar. However, as the diameter of the type A mini-screw used in this study was 1.45 mm, which is smaller than that of types B and C, there are limitations to comparisons of absolute torque values.

Type B showed an increase in insertion torque value with the increase in cortical bone thickness. However, the increase in MIT between 1.5 mm and 2 mm was less than the increase between 1.0 mm and 1.5 mm. The diameter of the upper part of the screw increases slightly and transitions into the soft tissue contact area, which was measured to be approximately 1.5 mm. It is because of this part that cortical bone thickness and MIT increases. However, with cortical bone thicker than 1.5 mm, the increase of torque is reduced (Figure 6).

Type C also showed an increase in insertion torque with the increase in cortical bone thickness, which was more evident than with type B. According to macroscopic measurements, the length of the tapered part was about 2.5 mm, which led to a significant increase in torque values within the 1.5-mm to 2-mm range (Figure 7).

Although many biomechanical studies have reported that insertion torque affects the stability of screws, it is difficult to assert that the insertion torque is proportional to the stability of mini-screws. Lawes et al[27] suggested that a high insertion torque of a tapered bone screw decreases loosening at the interface with bone. In contrast, Frost[28] mentioned that integrity could not be maintained if too much bone change occurred. Hansson and Werke[29] also mentioned that bone resorption occurs when forces are excessive and exceed the physiologic limit. In other words, when

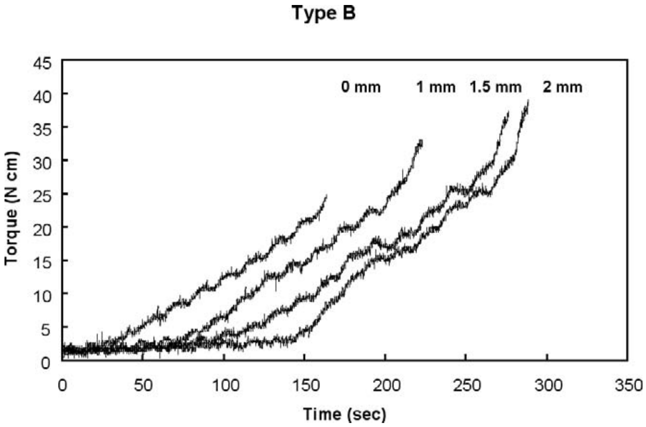

Figure 6. Superimposition of time-insertion torque graphs by cortical bone thickness in type B.

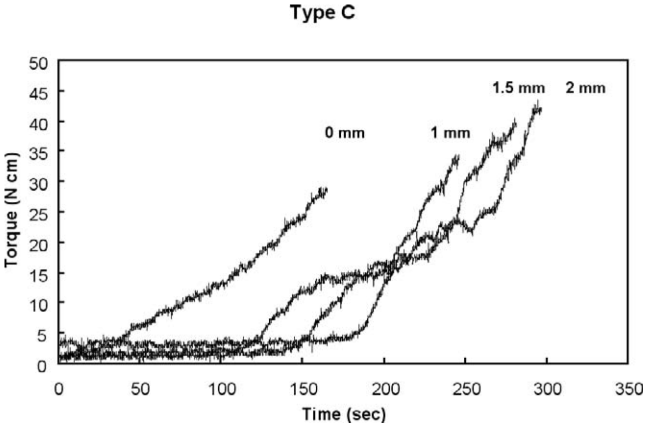

Figure 7. Superimposition of time-insertion torque graphs by cortical bone thickness in type C.

torque values are excessive and over the range of which the bone can withstand, bone cracks or bone necrosis may occur. This makes further studies necessary on the proper torque range that bone can withstand.

The MRT values of each screw type, according to the thickness of the cortical bone, tended to follow the pattern of the MIT value. The MRT values were lower than the MIT values in each type, and there was a so-called torque loss. This means that the torque value was not maintained as the screw was wound up. In other words, even if insertion was completed to the end of the screw thread where rotational force and torque value were at their highest, interfacial strain decreased as the screw is in equilibrium because of changes in the surrounding bone when the rotational force is removed.

The MRT value was higher in type B and type C than in type A, and torque loss was least in type A. This indicates that a taper-shaped structure not only affects the rise in torque value during insertion but also increases the torque loss range between the screw and the bone after implantation.

Studies using driving torque and artificial bone can be a good method of mechanical study of orthodontic mini-screws. However, even though the artificial bone used in this study is similar to human bone in physical characteristics, there will be some differences in torque value during insertion into vital bone. The mean MIT of mini-implant for the human subject was reported to range from 7.2 to 13.5 N cm, depending on the location, which was a lower MIT range than shown by our results.[30] In addition, the MRT measured immediately after placing implants into human cadavers ranged from 15.2 N cm to 21.4 N cm in 1.7 mm of mean cortical bone thickness.[31] Because of the difference in size and the insertion method of implant, however, there is a limitation to the comparison of the torque value between different study models.

In addition, as this study considered only the primary stability of the screw, which is related to initial fixation and is affected by mechanical characteristics of the mini-screw, more living tissue studies are required for a better understanding of secondary stability, which includes osteointegration and physiologic reactions of the bone to external forces. Henceforth, studies must be continued to find the proper torque values that minimize bone damage in the human body and act as sufficient anchorage for orthodontic forces in a range that the bone can withstand.

CONCLUSIONS

- A tapered form, especially a tapered form with the outer diameter increasing, is the design that increases the torque the most.
- The effect of cortical bone thickness on insertion torque was different depending on the screw type.
- Since the insertion torque of the taper form design increases with an increase in cortical bone thickness, a tapered screw needs to be chosen with a biomechanical adaptation level at the site of thick cortical bone.

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