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Original Article

Mechanical stability of orthodontic miniscrew depends on a thread shape

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KEYWORDS
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Abstract *Background/purpose:* Primary stability of orthodontic miniscrew system is of great importance in maintaining stable anchorage during a treatment period. Thus, this study aimed to examine whether the thread shape of orthodontic miniscrew had an effect on its mechanical stability in bone.
Materials and methods: Three different types of miniscrews (type A and B with a regular thread shape; type C with a novel thread shape) were placed in artificial bone block with different artificial cortical bone thickness of 1.5, 2.0 and 3.0 mm. Values of maximum insertion torque (MIT), removal torque (RT), torque ratio (TR), screw mobility, static stiffness (K), dynamic stiffness (K^*) and energy dissipation (tan δ) ability were assessed for each miniscrew system.
Results: The MIT, RT, TR and K of type C miniscrew were significantly greater than those of type A and B miniscrews when the miniscrews were placed in the thinner artificial bone. Furthermore, the TR value of type C miniscrew was more than 1, indicating the MRT value was larger than the MIT value in the novel miniscrew. The values of K^* and tan δ were almost similar among the three types of miniscrews.
Conclusion: The miniscrew with a novel thread shape showed a higher initial stability compared to those with a regular thread shape. Thus, in order to obtain a sufficient initial stability, it is important to select the type of screw thread that is appropriate for the thickness of the cortical bone.

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Introduction

Since appearance of miniscrews, the use of miniscrews has had an impact and has caused a paradigm shift in modern orthodontics. Despite their small diameter and short length, orthodontic miniscrews are very effective and useful tool for current orthodontic treatment.[1—3] Even without patients' cooperation, miniscrews can give secured anchorages for various tooth movements and even make it possible to move the tooth in directions which had been impossible with conventional orthodontic technique. On the contrary, the clinical application of miniscrews comes on some risks and concerns including miniscrew fracture, peri-implant tissue damage and miniscrew failure, which occur during screw insertion, at orthodontic force application, and during removal of screw, leading the delay of treatment term eventually.[4,5]

Even when miniscrew is properly placed, some screw may be failed. Failure rate of orthodontic miniscrews has been reported 10—30%, and considering that success rate of dental implants is approximately 96—99%, the success rate of orthodontic miniscrews is considerably lower.[6,7] Numerous factors have been reported so far in relation to screw failure. For the host factors, age, smoking, and oral hygiene control are reported as systemic factor, and implant site, cortical bone thickness, and bone density are present as local factors.[7—12] For the technical factors, screw thread shape, screw diameter, length, and taper, insertion method, torque, and angle, treatment time, magnitude and direction of orthodontic force are suggested.[11,13—19] These factors may occur in isolated or may be interrelated, interdependent, and coexistent. When two or more factors coexist, screw failure is more likely to occur; however, irrespective of host factors, most screw failures happen within one week after the implantation.[20,21] For screw failure occurring at the early period after implantation, screw loosening may be a main cause of screw failure. Hence, the screw loosening may be prevented by an improvement of screw structure.

In this line, we must consider enhancement of the mechanical stability immediately after screw placement, and increasing the success rate of miniscrews in clinical orthodontics is an urgent issue. Since it was reported that the screw thread shape influenced the resistance to pullout and, therefore, the primary stability of miniscrews,[19] we have developed a novel new miniscrew with different thread shape, by which the miniscrews are hardly loosened (Japanese patent No. 5904963). The novel thread of this miniscrew, contrary to the conventional types, has a larger area on the following flank than on the leading flank. Thus, the present study aims to evaluate the effect of the thread shape of orthodontic miniscrew on the mechanical stability. We hypothesize that a novel new orthodontic miniscrew with a locking thread structure has more mechanical stability than those with a regular thread shape.

Materials and methods

Miniscrews

For this study, three kinds of titanium miniscrews with the same screw diameter, 1.6 mm; and 6—7 mm screw length; were used: type A (Traditional thread shape with cylinder-type, Length, 7 mm; Absoanchor, Dentos Inc., Daegu, South Korea); type B (Traditional thread shape with tapered-type, Length, 6 mm; Thomas, DENTAURUM GmbH & Co. KG, Ispringen, Germany); and type C (Novel thread shape with tapered-type, Length, 7 mm; Type-TK, B-max Screw, BIO-DENT Co., Tokyo, Japan). Although we inserted all miniscrews to the artificial bone blocks until the supposed positions as clinical situation, these three miniscrews have different heights and locations of gingival area. Therefore, we didn't fully insert the type A and type C miniscrews to the artificial bone blocks. Thus, we selected and used type B miniscrew with the different screw length from the remaining two miniscrews to obtain the same insertion depth into the artificial bone block. In addition, the reason why we selected and used these three types of miniscrews was to evaluate the effect of not only thread shape but also taper on their mechanical parameters.

Total of 45 artificial bone blocks (Block 50 PCF; SawBones, Vashon Island, WA, USA) with a density of 0.8 g/cm^3 and different thickness were purchased and worked into a rectangular dimension with 15 mm × 13 mm: 1.5 mm, 2.0 mm, and 3.0 mm thick. Five of each type miniscrew were placed with self-tapping method into the artificial bone blocks. Briefly, the pre-drilling was made through the artificial bone block with a 1.0-mm twist drill at 500 rpm with continuous normal saline-solution irrigation. After making a guide hole with the same depth as the screw length, miniscrews were inserted by specific screw driver. All miniscrews were inserted 6 mm into the bone block (Fig. 1A).

Measurement of maximum insertion and removal torque

The artificial bone specimens were held by a custom made. This jig enables us to place the miniscrews in the same

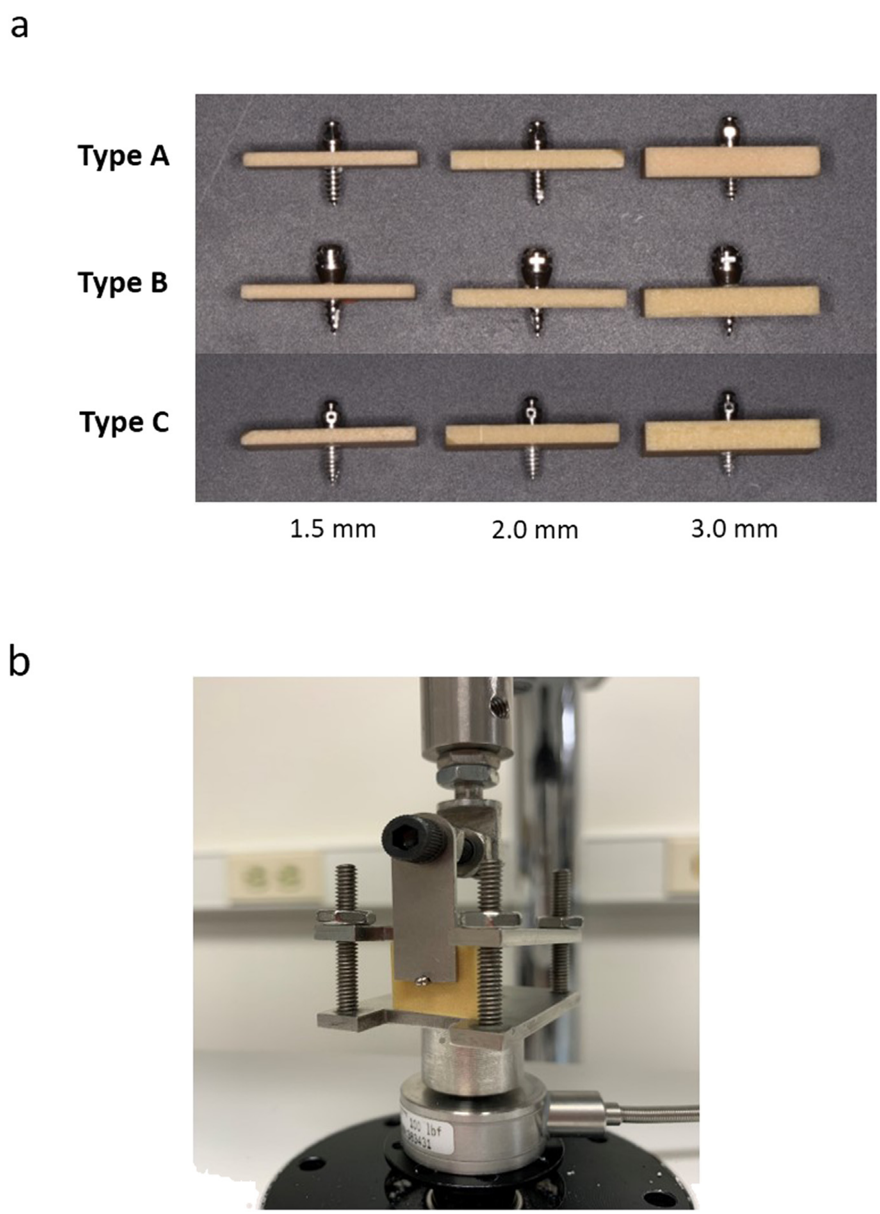


Figure 1 (a) Miniscrews installed at artificial bone with different thickness. (b) Experimental set-up for static and dynamic stiffness of the miniscrew system.

manner. After making a guide hole, the miniscrews were inserted at the center of artificial bone. Then, the artificial bones with the miniscrew were held in the jig, and the maximum insertion torque (MIT) of each miniscrew was gauged during the final screw tightening by a digital torque checker (DIS-RL05, Imada, Inc., USA). The maximum removal torque (MRT) was also gauged following static and dynamic mechanical tests. Furthermore, the torque ratio (TR) was calculated by dividing MRT by MIT.

Measurement of Periotest values

Measurements of screw mobility were blindly carried out by two experts with a sufficient skill for use in the Periotest M (Medizintechnik Gulden, Eshenweg, Germany). The Periotest is an electronic device that measures the damping characteristics of the interface between alveolar bone and implant. The tapping head in the handpiece bangs on the surface of the screw head at a rate of 4 times/sec. The contact time of the tapping head to the screw surface is calculated by the instrument, leading to the Periotest value as screw mobility. The Periotest values took an average value of three measurements taken at every quarter turn.

Static and dynamic stiffness measurement

After recording the Periotest values, the artificial bone specimens with miniscrews were placed onto a loading system (ElectroForce 3230, Bose, Minnetonka, MN, USA) composed of a 450 N load cell with a high resolution (15 nm) displacement transducer. After a −2 N preconditioning for establishing a tight contact of the loading jig to the screw

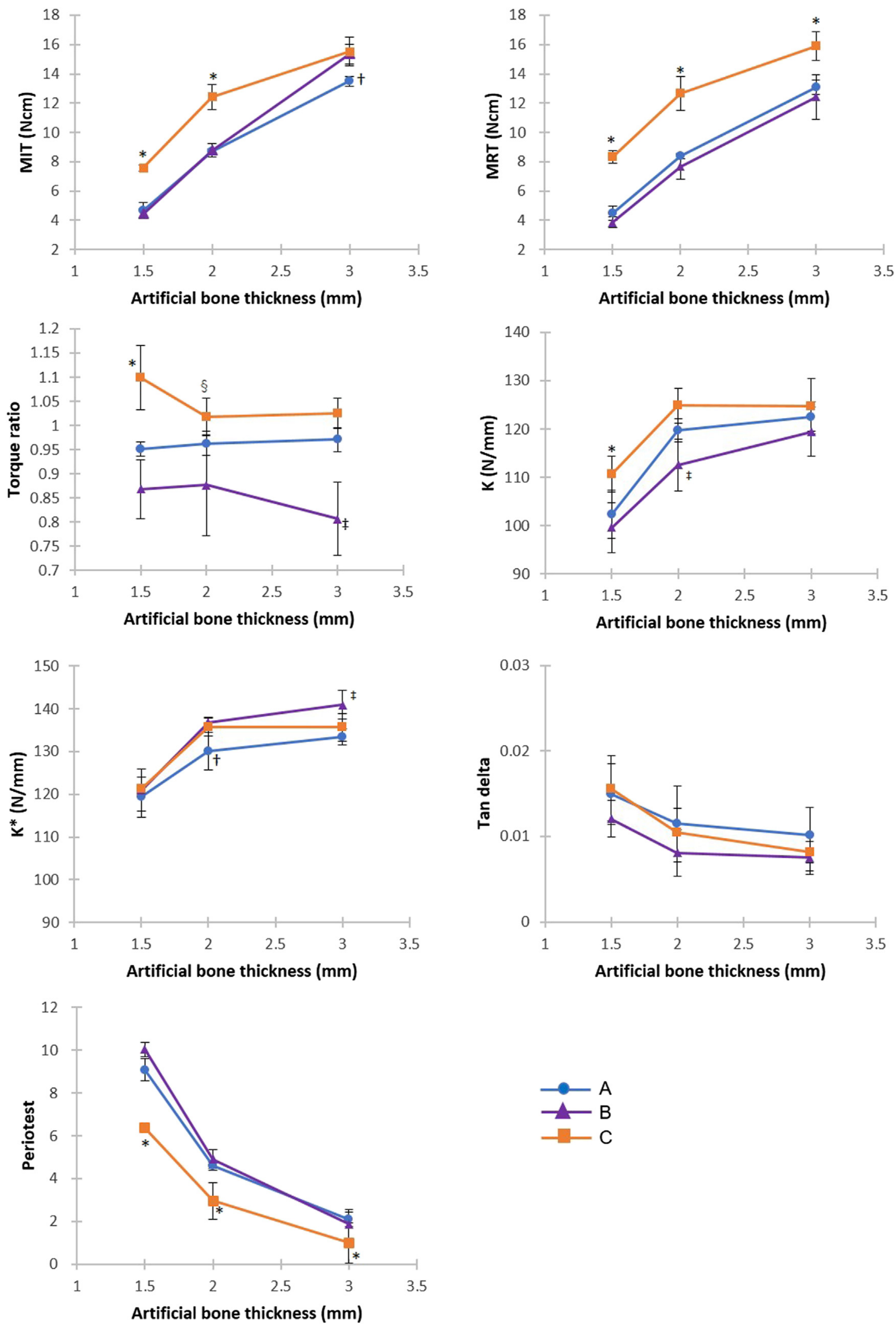


Figure 2 Comparison of mechanical parameters among the three types miniscrews installed at artificial bone blocks with 1.5, 2.0 and 3.0 mm thickness (n = 5 for each thickness). *$p < 0.05$ vs A and B with the same thickness; †$p < 0.05$ vs B and C with the same thickness; ‡$p < 0.05$ vs A and C with the same thickness; §$p < 0.05$ vs B with the same thickness.

surface, a tangential displacement with a steady rate of 0.01 mm/s was applied up to −0.02 mm perpendicular to the longitudinal screw axis (Fig. 1B). A static stiffness (K) was defined as the inclination of the initial load—displacement curve. After the static mechanical analysis, dynamic measurements were conducted. When a sinusoidal oscillating displacement was applied to the miniscrew with a dynamic amplitude of 0.005 mm at 0.5, 1.0, 2.0 and 3.0 Hz, dynamic behavior was obtained. According to the dynamic behavior of displacement and loading, the dynamic stiffness ($K*$), the storage stiffness (K'), the loss stiffness (K''), and the loss tangent tan δ are calculated as dynamic parameters. The dynamic stiffness $K*$ is decomposed into K' and K''. The storage stiffness K' indicates the elastic material behavior, while the loss stiffness K'' the viscous material behavior. The tan δ is defined to the ratio of the energy lost to that stored during a single cycle of deformation. The relationship among δ, K', and K" is determined by:

$$K* = \; + iK"; \; = |K*| \cos ?; \; K" = |K*| \sin \delta$$

where $I = \sqrt{-1}$ and δ is the phase angle. The tan δ is determined by dividing K'' by K'.

Statistical analysis

A two-way analysis of variance (ANOVA) was performed to assess interactions between miniscrew types and cortical bone thickness in determining values of each property (MIT, MRT, TR, Periotest, K, $K*$, tan δ) and a *post-hoc* Tukey HSD test was followed to compare those values. When the normality of the data distribution was confirmed, Pearson's correlation efficient was calculated to evaluate the correlation strength between the two variables associated with the mechanical behavior. For the data without normal distribution, Spearman's correlations of each measurement with those of the other variables were calculated. Analysis of covariance (ANCOVA) was performed to assess the correlation slope differences between the miniscrew types. Probabilities of <0.05 were considered to be significant.

Results

Mechanical parameters regarding mechanical stability of the miniscrew

The MIT values of type C miniscrew were significantly greater than those of type A and B miniscrews which were placed in bone plate with thinner cortical bone (1.5 mm and 2.0 mm) (Fig. 2). The type C miniscrew showed significantly higher MRT values than the type A and B miniscrews irrespective of the artificial bone thickness. As a consequence, the TR values were significantly higher in type C than in type A and B miniscrews with thinner cortical bone (1.5 mm thickness) (Fig. 2). Notably the TR values of type C miniscrew were more than 1, indicating the MRT value was larger than the MIT value in type C miniscrew.

The static stiffness of type C miniscrew was significantly greater than those of type A and B miniscrews when the miniscrews were placed in the artificial bone specimens with 1.5 mm thickness (Fig. 2). The values of dynamic stiffness and tan δ were almost similar among the three types of miniscrews; only when placing the miniscrews in the bone specimens with 2.0 mm thickness, type A miniscrews showed a significant lower dynamic stiffness than the remaining two types of miniscrews. This indicates that energy dissipation ability of the miniscrews was almost constant regardless of the cortical bone thickness and screw thread shape.

Periotest values were significantly lower in type C miniscrew regardless of the thickness of artificial bone specimens, indicating that screw mobility was significantly lower in type C miniscrew.

Correlations of static and dynamic stiffness with mechanical parameters

The values of K, $K*$ and Periotest had significant correlations with those of the other properties for three miniscrew types except those of tan δ in type A miniscrew (Fig. 3 and Table 1). The regression line slope of the relationship between MIT and MRT values was significantly different in type B miniscrew from those in type A and C miniscrews while the regression line slope of the other parameters was not significantly different (Fig. 3 and Table 1).

Discussion

Previously the influence of thread shape on miniscrew stability has been studied and reported by many researchers.[18,19,22–24] Gracco et al.[19] investigated the effects of variations in thread shape on the pullout strength of orthodontic miniscrews, and concluded that thread shape influenced the resistance to pullout of the orthodontic miniscrews and that the buttress reverse thread shape provided the highest pullout strength. Lee et al.[22] also evaluated the primary and long-term stability of dual-thread and cylindrical miniscrews, and demonstrated that the dual-thread miniscrew did not show superior long-term stability and clinical success rate as compared with the cylindrical miniscrews. Furthermore, Migliorati et al.,[18] using 60 miniscrews of 12 different types, evaluated the primary stability of different shaped miniscrews and indicated that bone characteristics such as cortical bone thickness and density play the major role in miniscrews primary stability while thread design showed no correlation. Therefore, no consensus has been reached on the optimal thread design of miniscrews. To derive an optimal design for screw thread, we developed 18 finite element models of miniscrews with varying screw diameter, taper, pitch at cortical and cancellous bone parts (double or single thread), and groove depth (unpublished data; Fig. 4). Two types of miniscrews with traditional and novel new threads were made by setting the proximal half angle at 0° or 35° and the distal half angle at 40° or 10°, respectively. The miniscrews had the following geometries; outer diameter, 1.6 mm; inner diameter, 1.2—1.4 mm; length, 6.0 mm; taper, 1° and 2°; thread width, 0.04 mm; pitch and depth, 0.2—0.5 mm and 0.1—0.2 mm for cortical bone site, and 0.5—0.8 mm and 0.2—0.3 mm for cancellous bone site, respectively. The results obtained were evaluated using Taguchi method that is robust design with higher reliability

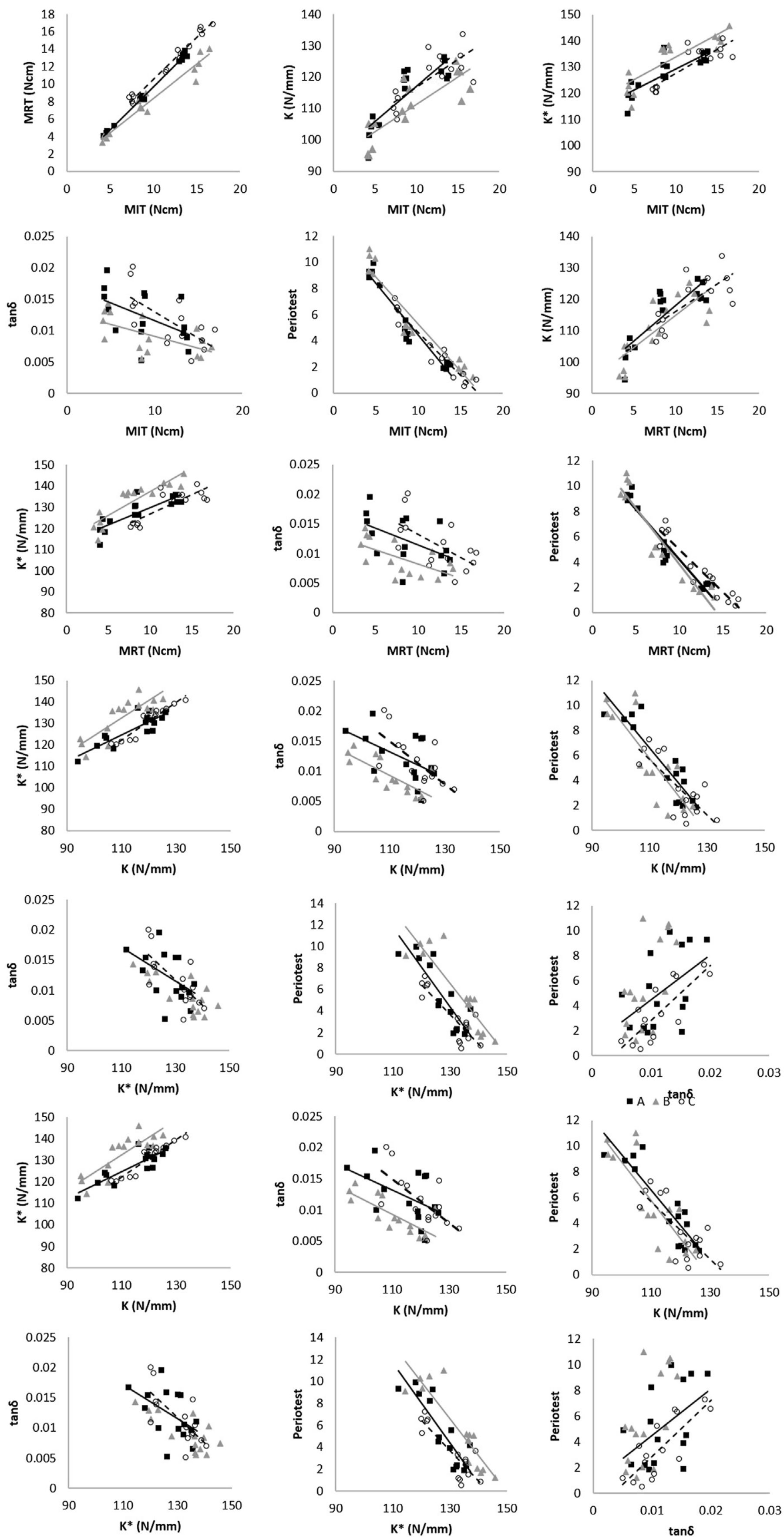


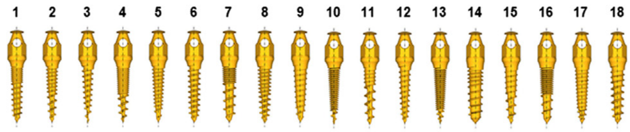
Figure 3 Mutual correlations of mechanical parameters. ■ type A; ▲ type B; ○ type C.

Table 1 Slope of the regression line of the relationship between the mechanical parameters.

X	Y	Miniscrew	Correlations	r	p value
MIT (N·cm)	MRT (N·cm)	A	Y = 0.981x - 0.144	0.998	<0.001
		B	Y = 0.783x + 0.528	0.975	<0.001
		C	Y = 0.952x + 1.027	0.99	<0.001
	K (N/mm)	A	Y = 2.253x + 94.696	0.854	<0.001
		B	Y = 1.726x + 94.077	0.825	<0.001
		C	Y = 1.748x + 99.394	0.752	<0.001
	K* (N/mm)	A	Y = 1.599x + 113.30	0.828	<0.001
		B	Y = 1.719x + 116.52	0.85	<0.001
		C	Y = 1.811x + 109.44	0.851	<0.001
	tanδ	A	Y = −0.0006x + 0.0173	−0.518	0.047
		B	Y = −0.0004x + 0.0129	−0.601	0.018
		C	Y = −0.0009x + 0.0215	−0.69	<0.001
	Periotest	A	Y = −0.785x + 12.284	−0.966	<0.001
		B	Y = −0.721x + 12.484	−0.954	<0.001
		C	Y = −0.655x + 11.196	−0.963	<0.001
MRT (N·cm)	K (N/mm)	A	Y = 2.279x + 95.173	0.85	<0.001
		B	Y = 2.068x + 94.016	0.793	<0.001
		C	Y = 1.765x + 98.388	0.73	<0.001
	K* (N/mm)	A	Y = 1.614x + 113.66	0.822	<0.001
		B	Y = 2.213x + 115.23	0.878	<0.001
		C	Y = 1.814x + 108.59	0.82	<0.001
	tanδ	A	Y = −0.0006x + 0.0172	−0.521	0.047
		B	Y = −0.0005x + 0.0131	−0.613	0.015
		C	Y = −0.0008x + 0.0211	−0.611	0.016
	Periotest	A	Y = −0.794x + 12.119	−0.96	<0.001
		B	Y = −0.888x + 12.702	−0.943	<0.001
		C	Y = −0.668x + 11.654	−0.944	<0.001
K (N/mm)	K* (N/mm)	A	Y = 0.623x + 56.011	0.851	<0.001
		B	Y = 0.815x + 42.886	0.843	<0.001
		C	Y = 0.877x + 25.579	0.958	<0.001
	tanδ	A	Y = −0.0002x + 0.0367	−0.514	0.049
		B	Y = −0.0002x + 0.0349	−0.761	<0.001
		C	Y = −0.0004x + 0.0541	−0.669	<0.001
	Periotest	A	Y = −0.278x + 37.232	−0.903	<0.001
		B	Y = −0.301x + 38.895	−0.834	<0.001
		C	Y = −0.222x + 30.069	−0.758	<0.001
K* (N/mm)	tanδ	A	NS	−0.501	0.057
		B	Y = −0.0002x + 0.0409	−0.756	0.001
		C	Y = −0.0004x + 0.0665	−0.725	<0.001
	Periotest	A	Y = −0.367x + 52.076	−0.872	<0.001
		B	Y = −0.336x + 50.279	−0.899	<0.001
		C	Y = −0.275x + 39.416	−0.86	<0.001
tanδ	Periotest	A	NS	0.483	0.068
		B	Y = 762.61x - 1.423	0.644	<0.001
		C	Y = 438.55x - 1.567	0.796	<0.001

in the field of quality engineering.[25,26] The Taguchi method is a powerful engineering tool for experimental optimization and one of the well-known robust design methods.[27] We evaluated the objective function of the optimum parameters using the signal-to-noise (S/N) ratio based on the-larger-the-better. According to the evaluation by the robust design, we found important factors for its stability and reliability and determined the final design for a novel new miniscrew. Compared to the traditional screw thread shape, the novel new screw thread showed almost similar value of the S/N ratio. Among the parameters, screw diameter, taper, and depth in cortical part play a crucial role in the screw stability and sensitivity. The miniscrew with smaller diameter and taper might be stable and ideal. With respect to the pitch and depth of screw thread at the cortical part, larger might be better for stability and sensitivity. The type C miniscrew has been developed based on the data from robust design.

Inoue et al.[6] measured the MIT and MRT at the miniscrew placement using a digital torque gauge, and demonstrated that neither MRT nor MIT affected the success rates of miniscrews although MRT had a positive correlation with MIT.



Design factors

	Thread shape	Diameter (mm)	Cortical bone Pick (mm)	Cortical bone Depth (mm)	Cortical bone Range (mm)	Cancellous bone Pick (mm)	Cancellous bone Depth (mm)
1	Traditional	1.2	0.20	0.10	1.5	0.50	0.20
2	Traditional	1.2	0.35	0.15	2.5	0.65	0.25
3	Traditional	1.2	0.50	0.20	4.0	0.80	0.30
4	Traditional	1.3	0.20	0.10	2.5	0.65	0.30
5	Traditional	1.3	0.35	0.15	4.0	0.80	0.20
6	Traditional	1.3	0.50	0.20	1.5	0.50	0.25
7	Traditional	1.4	0.20	0.15	1.5	0.80	0.25
8	Traditional	1.4	0.35	0.20	2.5	0.50	0.30
9	Traditional	1.4	0.50	0.10	4.0	0.65	0.20
10	Novel new	1.2	0.20	0.20	4.0	0.65	0.25
11	Novel new	1.2	0.35	0.10	1.5	0.80	0.30
12	Novel new	1.2	0.50	0.15	2.5	0.50	0.20
13	Novel new	1.3	0.20	0.15	4.0	0.50	0.30
14	Novel new	1.3	0.35	0.35	1.5	0.65	0.20
15	Novel new	1.3	0.50	0.50	2.5	0.80	0.25
16	Novel new	1.4	0.20	0.20	2.5	0.80	0.20
17	Novel new	1.4	0.35	0.10	4.0	0.50	0.25
18	Novel new	1.4	0.50	0.15	1.5	0.65	0.30

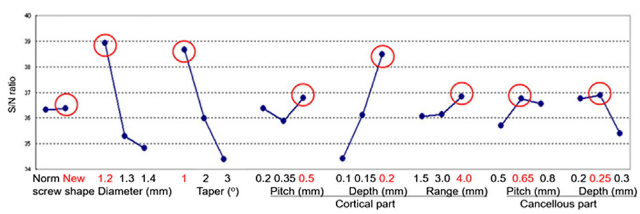


Figure 4 Evaluation results by robust design using the Taguchi statistical method. Eighteen finite element models of with different screw designs were constructed with varying thread shape, screw diameter, taper, pitch and depth at cortical and cancellous bone parts. The objective function of the optimum parameters was evaluated using signal-to-noise (S/N) ratio. Red circles and marks indicated an optimum value for each parameter.

On the contrary, the value of TR was significantly higher in the success group than in the failure group, indicating that the values of TR have a significant correlation with the miniscrew success rate. This implies that TR is a predictable factor for primary stability of miniscrews. Kim et al.[28] also demonstrated that the stability of miniscrews might be more related to the MRT than MIT. Our result showed significant positive relationships of static stiffness (K) to MIT and MRT irrespective of screw type. The K accounts for the initial stability of miniscrew system when the orthodontic wire is applied in the tangential direction to the miniscrew.[29] Thus, our result means that initial stability increases with an increment of MIT and MRT values. Furthermore, MIT and MRT increased with the thickness of artificial bone irrespective of screw type; however, type C miniscrew revealed the highest MIT and MRT values compared to type A and B miniscrews irrespective of artificial bone thickness. In addition, TR was significantly higher in type C miniscrew than in type A and B miniscrews and only type C miniscrew showed more than 1 of TR value regardless of artificial bone thickness. Since the high TR may be related to the high mechanical efficiency,[28,30] our results indicate that type C miniscrew may be easy for insertion but hardly loosened after its insertion. Previous studies[28,30] indicated TR was smaller than 0.5 when the miniscrew was inserted in the artificial bone with the self-drilling method, while TR was larger than 0.5 in most patients including the failure cases. This may be due to the differences of mechanical properties between human bone and artificial bone.

The value of tan δ is commonly used to evaluate visco-elastic behavior of a material.[31] The viscoelasticity of alveolar bone is a principal cause of energy dissipation.[32] With no or less ability of energy dissipation, storage of excessive strain energy into the miniscrew system can lead to breakage of alveolar bone and screw fracture. The miniscrew system used in the present study composes of elastic minicsrew and viscoelastic artificial cortical bone. The tan δ values commonly express dissipated energy associated with mobility due to interspace between the miniscrew and bone under cyclic loading. All three miniscrews showed similar values of tan δ ranging from 0.008 to 0.015, and the tan δ values decreased slightly with an increase of artificial bone thickness. Moreover, the values of tan δ had significant negative correlations with static stability; however, the slope of the regression line was steeper in type B miniscrew than in type A and C miniscrews. These findings indicate that type B miniscrew has a sufficient initial stability when the miniscrew was placed in the thicker cortical bone thicker. Type A and C miniscrews might be commonly better to obtain a sufficient initial stability irrespective of cortical bone thickness.

In conclusion, the present study provides the evidence of the beneficial effects of a novel new miniscrew with the different thread shape on the mechanical stability. Compared to the miniscrews with a regular thread shape, the novel miniscrew with a different thread shape shows a higher torque ratio and screw mobility which are important for the miniscrew initial stability. Taken into these considerations, it might be important to select the type of screw thread that is appropriate for the thickness of the cortical bone in order to obtain a sufficient initial stability.

Declaration of competing interest

KU and ET received patent royalty from BIODENT Co. All other authors state that they have no conflicts of interest.

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