

Mechanical Indicators of Primary Stability of Orthodontic Miniscrews: Effects of Pilot-Hole Diameter Across Three Commercial Systems with Different Thread External Diameters and Designs: An In Vitro Study

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Abstract

Background: Pre-drilling of pilot holes has been suggested to facilitate miniscrew placement in dense palatal bone. **Objective:** To compare mechanical indicators of primary stability (maximal insertion torque and pull-out strength) of miniscrew systems with different thread external diameters under varying pre-drilled pilot-hole diameters. **Materials and methods:** This study included 120 titanium alloy miniscrew implants with a thread length of 6.0 mm. The implants were classified into three groups according to thread external diameter (1.8, 1.9, and 2.0 mm). Each group was subdivided into four pilot-hole conditions: 0.0 mm (control), 1.1 mm, 1.2 mm, and 1.3 mm. All implants were inserted into synthetic composite palatal bone. Primary stability was evaluated by maximum insertion torque and vertical pull-out strength. **Results:** Both miniscrew system group and pre-drilled pilot-hole diameter significantly affected maximal insertion torque and pull-out strength ($P < 0.001$). A significant interaction between miniscrew system/design group and pilot-hole diameter was observed ($P < 0.001$). Maximal insertion torque decreased as pilot-hole diameter increased across all systems. The 2.0-mm system/design group consistently demonstrated the highest insertion torque under all drilling conditions. Pull-out strength remained relatively stable at 1.1-1.2 mm pilot-holes in the 1.8 mm system, whereas larger pilot-hole diameters resulted in significant reductions in some systems/designs. **Conclusion:** Both miniscrew implant design and pre-drilled pilot-hole diameter influence primary stability. Pilot-hole diameters of 1.1–1.2 mm provide an optimal balance between insertion torque and pull-out strength for 1.8–2.0 mm diameter miniscrews; however, the ideal pilot-hole size should be determined according to the specific miniscrew implant design.

Keywords: Insertion torque, Miniscrew implant, Palatal bone, Pre-drilled pilot-hole, Pull-out strength

Received: 4-Feb-2026 **Revised:** 4-Mar-2026 **Accepted:** 17-Mar-2026

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Introduction

Application of temporary anchorage devices, particularly miniscrew implants may expand the possibilities of orthodontic treatment, such as molar distal movement, incisor and molar intrusion, en-masse retraction, and complete arch distalization.^{1,2} The thread shape of miniscrew implants can affect their resistance to removal when the miniscrew implant's diameter, length, and bone characteristics remain constant. Gracco et al. investigated five different thread shapes: 1) buttress reverse, 2) buttress, 3) 75° joint profile, 4) round, and 5) trapezoid. Their findings indicated that the buttress reverse thread provided the highest pull-out resistance, suggesting the greatest primary stability,³⁻⁵ followed by the 75° joint profile thread. The superior resistance of the buttress reverse design may be explained by the inclination of the thread toward the implant head. These results are consistent with other studies reporting that thread angles between 45° and 90° enhanced miniscrew implant stability.^{4,6-8}

Palatal bone has been suggested as a suitable site for miniscrew implant placement because of its characteristics, such as thick and dense cortical bone, few vital anatomical structures, and an abundance of keratinized tissue. However, difficulty in miniscrew implant placement in dense palatal bone has been reported.⁹⁻¹¹ Over-tightening during placement might cause microfractures or necrosis of the surrounding bone.¹²⁻¹⁶ Accordingly, the use of a pre-drilled pilot hole has been suggested for miniscrew implant placement, particularly in dense palatal sites. Several factors influence the primary stability of miniscrew implants—commonly assessed by insertion torque and pull-out strength—including bone density, insertion angle, thread outer diameter, thread length, drilling protocols (e.g., pre-drilled pilot holes), and, importantly, the shape and design of the implant thread.^{7,17-22} The diameter of miniscrews has also been reported to influence primary stability. Larger diameters generally increase the bone-implant

contact area and mechanical retention, resulting in higher insertion torque and greater resistance to displacement. However, an increased diameter may also elevate insertion stress and the risk of cortical bone damage. Therefore, evaluating the effects of different external diameters under standardized conditions is clinically relevant.^{3,14,23}

In this study, maximal insertion torque and pull-out strength were used as mechanical indicators reflecting primary stability rather than direct measurements of primary stability. Therefore, the pre-drilled pilot-hole insertion technique is recommended for placing miniscrew implants into thick and dense cortical palatal bone in order to reduce compression at the thread-bone interface. However, as the diameter of the pre-drilled pilot hole increases, insertion torque decreases, resulting in reduced primary stability.^{24,25} Our previous study suggested that pre-drilled pilot holes with diameters of 1.1 mm and 1.2 mm (corresponding to 62 % and 67 % of the implant thread external diameter) provided optimal primary stability and were recommended for the placement of 1.8 × 6.0 mm (thread external diameter × length) titanium alloy implants in synthetic palatal bone.²⁶ The present in vitro study aimed to assess and compare the primary stability of miniscrew implants with three different thread external diameters during placement with pre-drilled pilot holes.

Materials and methods

This in vitro comparative study involved 120 miniscrew implants with a uniform thread length of 6.0 mm, categorized into three groups according to thread external diameter. Each group was further subdivided based on pre-drilled pilot-hole diameter for the measurement of maximum insertion torque and vertical pull-out strength, as follows.

The sample size of $n = 10$ per subgroup was based on previous in vitro studies evaluating miniscrew

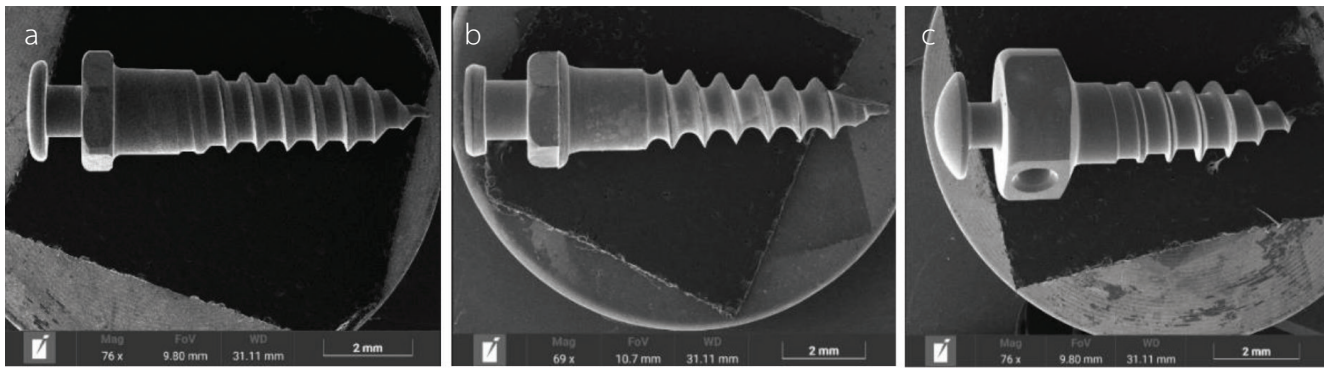


Figure 1 Scanning Electron microscope pictures of (a) Osstem miniscrew implant; 6-mm long with 1.8-mm outer diameter, (b) RJ (Rajavithi) miniscrew implant; 6-mm long with 1.9-mm outer diameter, and (c) Syntec miniscrew implant; 6-mm long with 2.0-mm outer diameter

mechanical stability and was considered sufficient to detect significant differences under controlled experimental conditions.

Group A forty titanium alloy miniscrew implants (Osstem Implant Co., Seoul, Korea: thread external diameter, 1.8 mm; length, 6.0 mm) (Figure 1a) were divided into four subgroups ($n = 10$ per subgroup), as follows: pre-drilled subgroup A1 (0.0 mm or no pre-drilled pilot-hole as negative control), pre-drilled subgroup A2 (1.1 mm pre-drilled pilot-hole or 61.10 %), pre-drilled subgroup A3 (1.2 mm pre-drilled pilot-hole or 66.70 %), and pre-drilled subgroup A4 (1.3 mm pre-drilled pilot-hole or 72.20 %). The percentage in parentheses represented the ratio between the pre-drilled pilot-hole diameter and the external thread diameter of the investigated miniscrew implant.

Group B forty titanium alloy miniscrew implants (RJ, Rajavithi Hospital, Thailand: thread external diameter, 1.9 mm; length, 6.0 mm) (Figure 1b) were divided into four subgroups ($n = 10$ per subgroup), as follows: pre-drilled subgroup B1 (0.0 mm or no pre-drilled pilot-hole as negative control), pre-drilled subgroup B2 (1.1 mm, pre-drilled pilot-hole or 57.90 %), subgroup B3 (1.2 mm, pre-drilled pilot-hole or 63.20 %) and pre-drilled subgroup B4 (1.3 mm pre-drilled pilot-hole or 68.40 %).

Group C forty titanium alloy miniscrew implants (Syntec Scientific Corporation, Taiwan: thread external diameter, 2.0 mm; length, 6.0 mm) (Figure 1c) were divided into four subgroups ($n = 10$ per subgroup), as follows: pre-drilled subgroup C1 (0.0 mm or no pre-drilled pilot-hole as negative control), pre-drilled subgroup C2 (1.1 mm pre-drilled pilot-hole or 55.0 %), pre-drilled group C3 (1.2 mm pre-drilled pilot-hole or 60.0 %) and pre-drilled group C4 (1.3 mm pre-drilled pilot-hole or 65.0 %).

The RJ miniscrew showed the greatest neck length (1.79 mm), widest thread pitch (0.80 mm), and deepest thread depth (0.37 mm), indicating a more aggressive thread design. The Osstem system demonstrated intermediate values (neck length 1.51 mm, thread pitch 0.69 mm, thread depth 0.25 mm), whereas the Syntec miniscrew exhibited the smallest neck length (0.93 mm) and shallowest thread depth (0.22 mm), suggesting a less pronounced thread profile.

In our previous study, synthetic composite bone blocks (Sawbones®, Pacific Research Laboratories, Inc., Vashon, WA, USA) were used. To simulate human palatal bone, a 2.0-mm-thick layer of 40 pcf (0.64 g/cc) epoxy-reinforced polyurethane (cortical bone) was attached to a 12.0-mm-thick block of 20 pcf (0.32 g/cc) rigid polyurethane (cancellous bone). A custom-made

instrument-holding system was used to position the digital torque gauge (IMADA Inc., Northbrook, IL, USA) and the synthetic bone blocks to ensure a consistent direction of the pre-drilled pilot-hole line and implant insertion path.⁶

Pre-drilled pilot-holes with diameters of 1.1, 1.2, and 1.3 mm were prepared manually using the corresponding drill bits to a standardized depth of 5.0 mm. The drill bits were secured in the chuck of a digital torque gauge attached to a custom-made instrument-holding system. To control the pilot-hole depth, a color-coded stop was positioned 5.0 mm from the drill-bit tip. The same protocol was applied to all three miniscrew groups (A, B, and C) and to all pre-drilled pilot-hole subgroups (2, 3, and 4), corresponding to the 1.1-, 1.2-, and 1.3-mm drill bits.

For the maximum insertion torque assessment, cubical Sawbones® blocks in the control group were fixed in a custom-made synthetic bone holder, which was rigidly secured to one of the instrument-holding system's bearings. A miniscrew implant was attached to the digital torque gauge via the implant screwdriver shaft. A red line was drawn on the torque-gauge holder of the holding system 5.0 mm from its edge as a stop mark. The implant was driven 5.0 mm into the bone block (not the entire thread length) at a constant speed of twelve rotations per minute until the edge of the torque-gauge holder reached the red line. The maximum insertion torque was then recorded. The same protocol was applied to the previously drilled synthetic bone.²⁶

After the maximum insertion torque tests, the synthetic bone cube was transferred and rigidly fixed to the inferior clamp of a Universal Testing Machine (Instron Corp., Canton, MA, USA). The miniscrew implant was secured using a pulling apparatus attached to the superior clamp of the Universal Testing Machine. The test was performed with a 500 N load cell. A vertical force was applied parallel to the long axis of the implant at a crosshead speed of 10 mm/min until the implant was detached from the block. The maximum

force at the moment of implant detachment was defined as the pull-out strength.² The details of the measurement method were already described in our previous publication.²⁶

Statistical analysis

Data were analyzed using SPSS software (version 17.0; SPSS Inc., Chicago, IL, USA). Data normality was assessed using the Kolmogorov–Smirnov test, which confirmed normal distributions across all twelve subgroups ($P > 0.05$). Given the overall distribution and the robustness of ANOVA to mild violations of normality, parametric analyses were performed. When significant differences were detected, multiple comparisons were conducted using Tukey's honestly significant difference (HSD) post hoc test. Means and standard deviations of maximal insertion torque and pull-out strength were calculated.

Results

Maximal insertion torque

The means and standard deviations of maximal insertion torque are presented in Figure 2. The data met the assumptions for parametric analysis. Two-way ANOVA revealed significant main effects of miniscrew system group and pilot-hole diameter on maximal insertion torque (both $P < 0.001$), as well as a significant interaction between these factors ($P < 0.001$) (Table 1). Overall, maximal insertion torque decreased as pilot-hole diameter increased across all miniscrew systems.

Within-group comparisons by pilot-hole diameter

Group A (Osstem, external diameter 1.8 mm)

Maximal insertion torque decreased progressively from the control group to larger pilot holes (0.0 mm: 11.58 ± 0.38 Ncm; 1.1 mm: 9.49 ± 0.37 Ncm; 1.2 mm: 8.46 ± 0.33 Ncm; 1.3 mm: 7.55 ± 0.32 Ncm). Tukey's test showed that maximal insertion torque was

Table 1 Two-way ANOVA (Type III sums of squares) evaluating the effects of miniscrew system/design group, pilot-hole diameter, and their interaction on maximal insertion torque (Ncm).

	df	Sum of squares	Mean square	F ratio	P value
Miniscrew system group	2	325.66	162.83	382.85	< 0.001***
Pilot-hole diameter	3	409.09	136.36	320.62	< 0.001***
System × pilot-hole diameter	6	20.63	3.43	8.08	< 0.001***
Error	108	45.93	0.42		

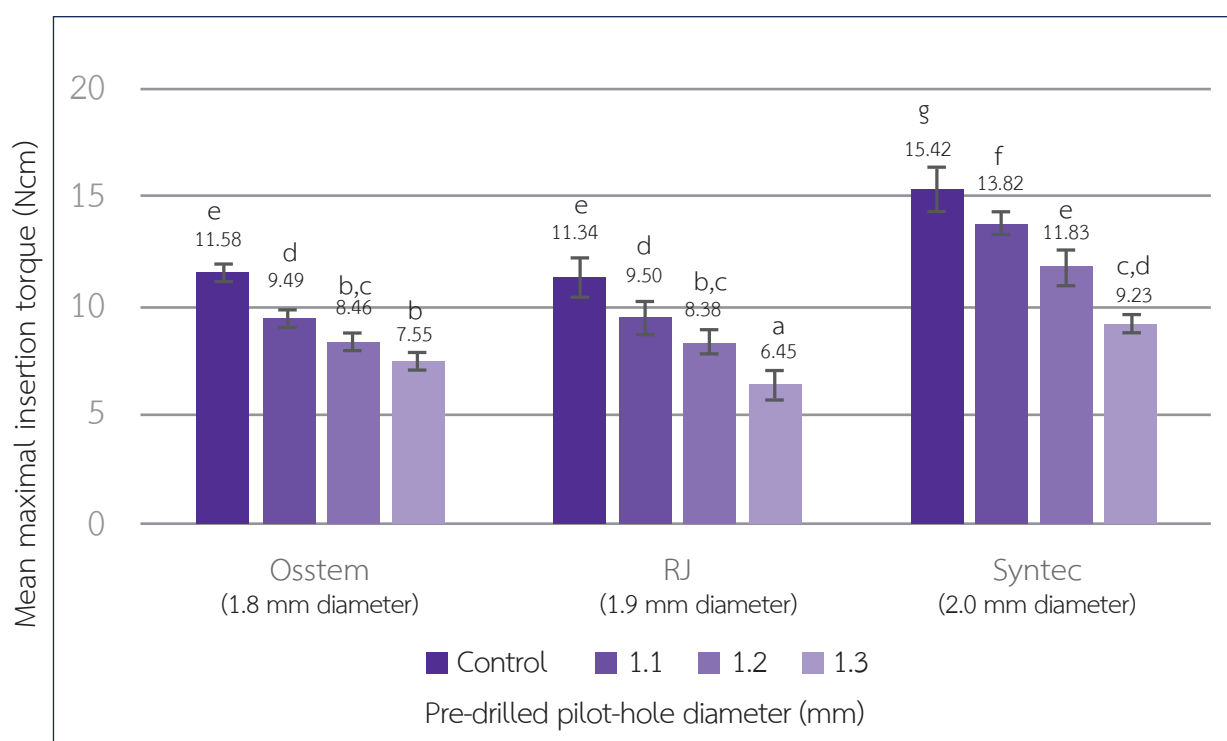


Figure 2 Mean ($\pm$ SD) maximal insertion torque (Ncm) for three miniscrew systems (Osstem 1.8 mm, RJ 1.9 mm, and Syntec 2.0 mm) inserted into synthetic composite palatal bone using pilot-hole diameters of 0.0 mm (control), 1.1 mm, 1.2 mm, and 1.3 mm. Superscript letters indicate pairwise comparisons across all 12 system $\times$ pilot-hole combinations using Tukey's HSD ($P < 0.05$). Bars sharing at least one letter are not significantly different.

significantly greater in the control condition compared with all pre-drilled conditions ($P < 0.001$). The post-hoc test also confirmed that there were significant differences in maximal insertion torque associated with pre-drilled pilot-hole diameters ($P < 0.001$).

Group B (RJ, external diameter 1.9 mm)

A similar decreasing trend was observed (0.0 mm: 11.34 ± 0.91 Ncm; 1.1 mm: 9.50 ± 0.80 Ncm; 1.2 mm: 8.38 ± 0.56 Ncm; 1.3 mm: 6.45 ± 0.66 Ncm). Tukey's test showed that maximal insertion torque was significantly greater in the miniscrew implant

inserted without using pre-drilled pilot-holes than in those inserted with using pre-drilled pilot-holes. The differences between the control group and the groups with 1.1-mm, 1.2-mm and 1.3-mm pre-drilled pilot-hole diameters were also statistically significant ($P < 0.001$). The post-hoc test also confirmed that there were significant differences in maximal insertion torque associated with pre-drilled pilot-hole diameters ($P < 0.001$).

Group C (Syntec, external diameter 2.0 mm)

Syntec demonstrated the highest torque values across drilling conditions, with a consistent decline as pilot-hole diameter increased (0.0 mm: 15.42 ± 1.02 Ncm; 1.1 mm: 13.82 ± 0.59 Ncm; 1.2 mm: 11.83 ± 0.85 Ncm; 1.3 mm: 9.23 ± 0.45 Ncm). Tukey's test showed that maximal insertion torque was significantly greater in the miniscrew implant inserted without using pre-drilled pilot-holes than in those inserted with using

pre-drilled pilot-holes. The differences between the control group and the groups with 1.1-mm, 1.2-mm and 1.3-mm pre-drilled pilot-hole diameters were also statistically significant ($P < 0.001$). The post-hoc test also confirmed that there were significant differences in maximal insertion torque associated with pre-drilled pilot-hole diameters ($P < 0.001$).

Between-group comparisons at each pilot-hole diameter

When comparing maximal insertion torque among three different miniscrew implant systems (Figure 2), Syntec consistently demonstrated significantly higher torque values than RJ and Osstem in all pre-drilled pilot-hole conditions. In the control group, Syntec showed the highest torque (15.42 ± 1.02 Ncm), while Osstem (11.58 ± 0.38 Ncm) and RJ (11.34 ± 0.91 Ncm) were comparable.

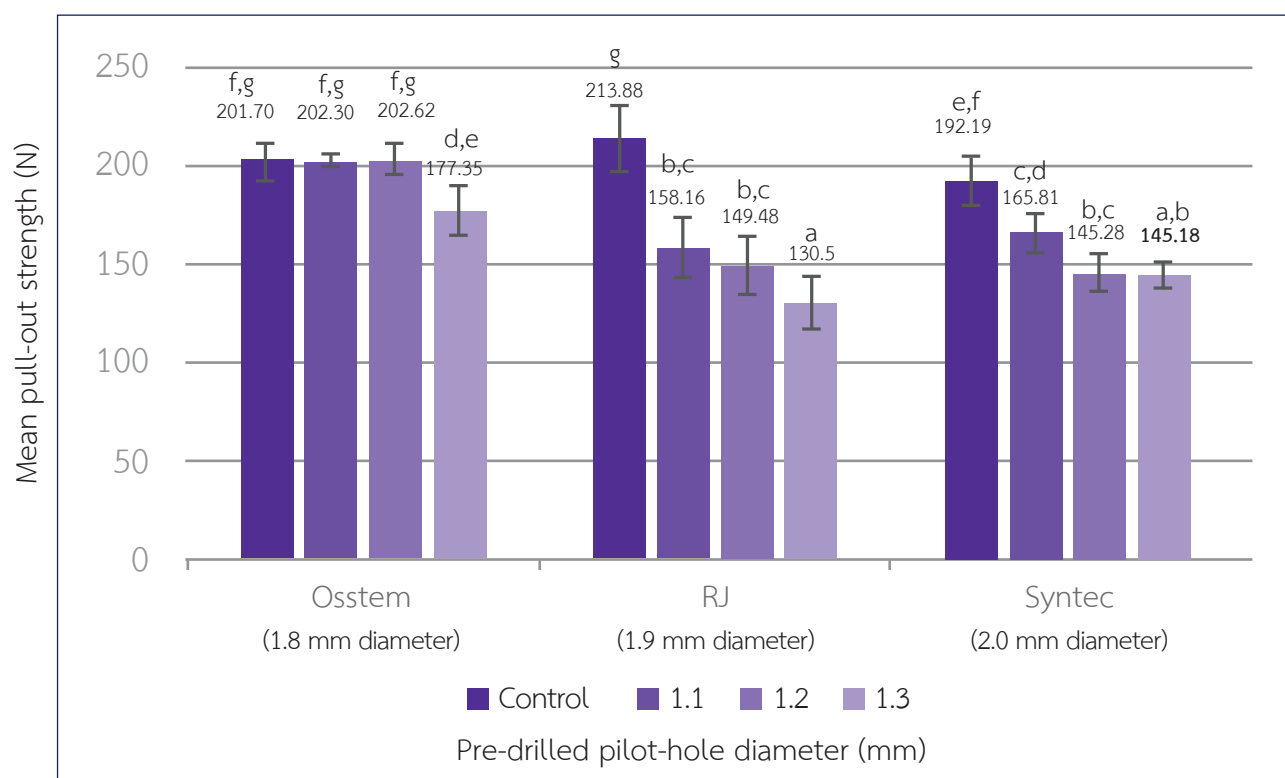


Figure 3 Mean ($\pm$ SD) pull-out strength (N) for three miniscrew systems (Osstem 1.8 mm, RJ 1.9 mm, and Syntec 2.0 mm) inserted into synthetic composite palatal bone using pilot-hole diameters of 0.0 mm (control), 1.1 mm, 1.2 mm, and 1.3 mm. Superscript letters indicate pairwise comparisons across all 12 system $\times$ pilot-hole combinations using Tukey's HSD ($P < 0.05$). Bars sharing at least one letter are not significantly different.

Table 2 Two-way ANOVA (Type III sums of squares) evaluating the effects of miniscrew system/design group, pilot-hole diameter, and their interaction on pull-out strength (N).

	df	Sum of squares	Mean square	F ratio	P value
Miniscrew system group	2	29,828.28	14,914.14	110.83	< 0.001***
Pilot-hole diameter	3	42,453.06	14,151.02	105.16	< 0.001***
System × pilot-hole diameter	6	15,591.42	2,598.57	19.31	< 0.001***
Error	108	14,532.43	134.56		

The same pattern was observed at 1.1 mm (Syntec: 13.82 ± 0.59 Ncm; RJ: 9.50 ± 0.80 Ncm; Osstem: 9.49 ± 0.37 Ncm), 1.2 mm (Syntec: 11.83 ± 0.85 Ncm; Osstem: 8.46 ± 0.33 Ncm; RJ: 8.38 ± 0.56 Ncm), and 1.3 mm (Syntec: 9.23 ± 0.45 Ncm; Osstem: 7.55 ± 0.32 Ncm; RJ: 6.45 ± 0.66 Ncm), with statistically significant differences between Syntec and the other groups at each drilling condition post hoc ($P < 0.001$) (Table 1).

Pullout strength

The means and standard deviations of pull-out strength are presented in Figure 3. The data met the assumptions for parametric analysis. Two-way ANOVA showed significant main effects of miniscrew system group and pilot-hole diameter on pull-out strength (both $P < 0.001$), with a significant interaction between factors ($P < 0.001$) (Table 2). Overall, pull-out strength tended to decrease as pilot-hole diameter increased, although the magnitude of reduction differed across miniscrew systems.

Within-group comparisons by pilot-hole diameter

Group A (Osstem, external diameter 1.8 mm)

Pull-out strength remained stable across the control and smaller pilot holes (0.0 mm: 201.70 ± 9.42 N; 1.1 mm: 202.30 ± 3.82 N; 1.2 mm: 202.62 ± 8.40 N),

but decreased at the largest pilot-hole diameter (1.3 mm: 177.35 ± 12.09 N). Tukey's test showed that the 1.1-mm and 1.2-mm groups demonstrated comparable pull-out resistance to the control, with no significant differences detected. A significant decrease was observed only in the 1.3-mm group compared with the control ($P < 0.001$). Post-hoc analysis confirmed that pre-drilled pilot-hole diameter significantly affected pull-out strength ($P < 0.001$).

Group B (RJ, external diameter 1.9 mm)

Pull-out strength decreased substantially with pre-drilling (0.0 mm: 213.88 ± 16.47 N; 1.1 mm: 158.16 ± 15.42 N; 1.2 mm: 149.48 ± 14.88 N; 1.3 mm: 130.50 ± 13.49 N). Tukey's test demonstrated that the control group exhibited significantly greater pull-out resistance than all pre-drilled groups ($P < 0.001$). All pre-drilled pilot-hole diameters resulted in significant reductions compared with the control group. The post-hoc test further confirmed significant differences in pull-out strength across pre-drilled pilot-hole diameters ($P < 0.001$).

Group C (Syntec, external diameter 2.0 mm)

Pull-out strength also decreased with increasing pilot-hole diameter (0.0 mm: 192.19 ± 12.58 N; 1.1 mm: 165.81 ± 9.58 N; 1.2 mm: 145.28 ± 9.44 N; 1.3 mm: 145.18 ± 6.46 N). Tukey's test revealed that the control group had significantly greater pull-out resistance than all pre-drilled groups ($P < 0.001$). Pull-out

strength decreased progressively with increasing pilot-hole diameter, and no significant difference was observed between the 1.2-mm and 1.3-mm groups. Post-hoc analysis confirmed that pre-drilled pilot-hole diameter had a significant effect on pull-out strength ($P < 0.001$).

Between-group comparisons at each pilot-hole diameter

When comparing pull-out strength among three different miniscrew implant systems, several significant inter-group differences were observed (Figure 3). In the control condition (0.0 mm), pull-out strengths were 201.70 ± 9.42 N (Osstem), 213.88 ± 16.47 N (RJ), and 192.19 ± 12.58 N (Syntec). RJ showed significantly greater pull-out strength than Syntec ($P < 0.05$), while Osstem did not differ significantly from either group.

At pilot-hole diameters of 1.1, 1.2, and 1.3 mm, Osstem consistently demonstrated the highest pull-out strength. In the 1.1-mm pre-drilled pilot-hole group, Osstem exhibited the highest pull-out strength (202.30 ± 3.82 N), which was significantly greater than RJ (158.16 ± 15.42 N) and Syntec (165.81 ± 9.58 N); RJ and Syntec did not differ significantly. For the 1.2-mm pre-drilled pilot-hole category, Osstem maintained the highest pull-out strength (202.62 ± 8.40 N), exceeding both RJ (149.48 ± 14.88 N) and Syntec (145.28 ± 9.44 N) with statistically significant differences. RJ and Syntec did not differ significantly from one another. A similar pattern was observed in the 1.3-mm pre-drilled pilot-hole category, where Osstem (177.35 ± 12.09 N) demonstrated significantly greater pull-out strength than RJ (130.50 ± 13.49 N) and Syntec (145.18 ± 6.46 N). Again, no significant difference was found between RJ and Syntec.

Discussion

One limitation of the present investigation relates to the study design and sample selection. The primary objective was to compare miniscrews with

three different thread external diameters; however, these diameters were not available within a single commercial system. Consequently, the three diameter groups were drawn from different manufacturers (Osstem 1.8 mm, RJ 1.9 mm, and Syntec 2.0 mm), and certain design-related variables (e.g., thread depth, pitch, taper, and core diameter) could not be fully controlled. Therefore, differences observed among the tested miniscrew groups should be interpreted as reflecting the combined effect of external diameter and system-specific thread design rather than external diameter alone. At the same time, this approach mirrors routine clinical decision-making, where clinicians choose among available commercial miniscrew systems rather than custom-manufactured implants with identical geometries, and thus may enhance the external validity of the findings.

The present study evaluated the influence of miniscrew system/design and pilot-hole diameter on two parameters of primary stability, insertion torque and pull-out strength, by comparing three different designs (Syntec, RJ, and Osstem). The results clearly demonstrated that both factors had statistically significant effects and, most importantly, that their interaction was significant ($P < 0.001$) for both torque and pull-out strength. This interaction suggests a synergistic relationship between thread geometry and pilot-hole preparation, consistent with previous reports indicating that variations in thread configuration can substantially modify bone engagement, compressive behavior, and mechanical interlock.^{25,27-30}

These findings expand upon our previous study, performed using Osstem screws alone, which concluded that 1.1–1.2 mm pilot-hole diameters (approximately 62–67 % of the outer diameter) provide an optimal balance between insertion torque and pull-out strength.²⁶ In the current investigation, Osstem again demonstrated relatively stable pull-out strength at 1.1–1.2 mm, even as insertion torque decreased progressively. The slightly higher mean pull-out strength in these groups compared

with the control may be attributed to the reduction of excessive compression during insertion. While high insertion torque is often associated with primary stability, it can also lead to localized microdamage of the surrounding material. Moderate pre-drilling may optimize thread engagement by preserving the structural integrity of the bone-thread interface, thereby maintaining or slightly improving mechanical interlock; however, this numerical difference was not statistically significant ($P > 0.05$). Furthermore, the fact that Syntec and RJ systems produced distinct patterns under the same protocol underscores that pilot-hole guidelines must be tailored to specific miniscrew designs rather than generalized.

For Syntec, insertion torque remained highest in the control (no pre-drill pilot-hole) and 1.1 mm groups and decreased markedly with larger pilot holes, suggesting that this design benefits from tighter bone engagement. In contrast, RJ screws exhibited a pronounced decline in both insertion torque and pull-out strength with increasing pilot-hole diameter, suggesting greater sensitivity to pilot-hole enlargement ('over-drilling') relative to the other systems. This pattern may reflect a stronger dependence on frictional retention and compressive engagement at the cortical layer in this synthetic bone model. These findings emphasize that a single pre-drilled pilot-hole guideline cannot be universally applied across different miniscrew implant thread design. Biomechanically, the differences can be attributed to variations in thread depth, pitch, and taper configuration, which collectively influence cortical bone compression and mechanical interlock.

From a clinical perspective, smaller pilot holes generally increase insertion torque and immediate mechanical stability; however, excessive torque may also increase cortical compression and microdamage, potentially compromising early stability, particularly when early loading is planned.¹⁴ Accordingly, moderate pre-drilled pilot-holes (1.1–1.2 mm) appear to offer a practical compromise, maintaining adequate stability

while minimizing cortical bone stress. Accordingly, moderate pre-drilled pilot-holes (1.1–1.2 mm) appear to offer a practical compromise, maintaining adequate stability while minimizing cortical bone stress, particularly for the 1.8–2.0 mm diameter miniscrews evaluated in this study. Overall, this study demonstrates that primary stability behavior is design-specific: Syntec responds optimally to smaller pilot-hole diameters, RJ is more sensitive to over-drilling, and Osstem remains relatively stable across the tested diameters. These interactions underscore the need for system-specific pilot-hole recommendations rather than a universal protocol.

The differences in thread geometry among the miniscrew systems may contribute to the variations observed in insertion torque and pull-out strength. Miniscrews with deeper and sharper thread profiles, such as the RJ system, may enhance mechanical interlocking with the surrounding material, resulting in greater resistance to dislodgement and higher pull-out strength. In contrast, the Syntec miniscrew, characterized by a relatively shallow thread depth and wider thread pitch, may provide reduced thread engagement and mechanical retention, potentially leading to lower pull-out resistance. Therefore, the mechanical performance of miniscrews should be interpreted with consideration of thread design as a potential cofactor influencing stability outcomes. However, further investigation is required to clarify the extent to which these geometric characteristics affect insertion torque and pull-out strength.

Several factors should be considered when translating these findings to clinical practice. The synthetic bilayer model provides standardized conditions but cannot fully reproduce the heterogeneity and viscoelastic behavior of human palatal bone, where cortical thickness and density vary by anatomical site and patient. In addition, miniscrews were inserted to a standardized depth of 5.0 mm rather than the full thread length, and pull-out testing was performed under purely axial loading; both factors

may influence the absolute values and limit direct clinical extrapolation. Future studies incorporating variation in cortical thickness, oblique and cyclic loading, and detailed geometric characterization of thread parameters (e.g., core diameter, pitch, thread depth, and taper) would help refine system-specific pilot-hole recommendations.

Conclusion

Miniscrew system/design group and pilot-hole diameter significantly affected maximal insertion torque and pull-out strength (all $P < 0.001$), with a significant system $\times$ pilot-hole interaction for both outcomes ($P < 0.001$), indicating design-dependent responses to pre-drilling. Syntec showed the highest insertion torque across conditions, Osstem maintained relatively stable pull-out strength at 1.1–1.2 mm, and RJ exhibited the greatest reductions with increasing pilot-hole diameter. Therefore, pilot-hole selection should be system-specific; 1.1–1.2 mm may represent a practical compromise across the tested systems.

Author contributions

Poomsthira Joitkashira: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration, Funding acquisition; **Prajak Jariyapongpaiboon:** Resources, Writing - Review & Editing; **Petchpailin Phusantisampan:** Methodology, Writing - Review & Editing; **Kachaphol Kuharattanachai:** Conceptualization, Methodology, Formal analysis, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition

Ethical statement

None.

Disclosure statement

The authors have no conflict of interest.

AI-assisted writing declaration

The authors used ChatGPT (OpenAI, GPT-5.5) solely for language editing and manuscript refinement. All scientific content was developed and verified by the authors, who take full responsibility for the accuracy, integrity, and originality of the manuscript.

Acknowledgements

The authors sincerely appreciated Dr. Thanapat Sastraruji, Faculty of Dentistry, Chiang Mai University, for his valuable assistance in statistical consultation. The authors also gratefully acknowledged Syntec Scientific Corporation, Taiwan, for providing the Syntec miniscrew implants for this investigation.

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