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Effects of Percutaneous Pedicle Screw Placement and Suboptimal Insertion Depth on Insertion Torque and Pullout Strength: A Biomechanical Analysis

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Abstract

Introduction: Screw pullout strength is a crucial measure of biomechanical pedicle screw performance and durability in vivo. Factors including screw design, insertion technique, and bone quality can significantly influence this. The effect of insertion depth on the biomechanical properties of percutaneous pedicle screws remains incompletely characterized.

Methods: A biomechanical assessment of screw insertion torque and axial pullout strengths was conducted using polyaxial pedicle screws (Viper Prime™, DePuy Synthes, PA, USA) and solid polyurethane foam vertebral bone analogues (20 PCF, Sawbones Inc., WA, USA). Three pedicle screw sizes were evaluated: 5mm diameter (45mm length), 6mm diameter (50mm length), and 7mm diameter (50mm length). A uniaxial linear-torsion testing machine (E10000, Instron Inc, MA, USA) was used to perform insertion and pull out according to ASTM F543 standard. Insertion torque was measured continuously up to full depth. Axial pull-out strength was measured starting with full depth insertion and gradually decreasing to a 10mm gap between screw head and the block surface, in steps of 1mm.

Results: Mean maximum insertion torques were 6.17 ± 0.50 Nm, 6.80 ± 2.70 Nm, and 9.85 ± 2.82 Nm for the 5mm, 6mm, and 7mm screws, respectively ($p = 0.039$). As the gap increased from 0 to 10mm, pull-out strength decreased from 1.62 ± 0.03 kN to 0.98 ± 0.02 kN in the 5mm screw, from 2.20 ± 0.10 kN to 1.71 ± 0.04 kN in the 6mm screw, and from 2.28 ± 0.27 kN to 1.75 ± 0.14 kN in the 7mm screw. Linear regression analysis revealed strong linear relationships ($R^2 = 0.580–0.908$, $p < 0.01$) between gap size and pullout strength for all screw diameters. Statistical analysis confirmed significantly greater pull-out strength for larger screws ($p < 0.0001$).

Conclusion: Larger diameter screws demonstrate significantly greater pullout strength. Increasing screw insertion depth is associated with progressively greater insertion torque and higher pullout strengths across all screw diameters assessed.

Introduction

Pedicle screw fixation is a cornerstone of modern spinal surgery, providing mechanical stability and facilitating successful spinal fusion [1, 2]. The percutaneous approach to pedicle screw insertion offers significant advantages over traditional open techniques, including reduced soft tissue trauma, decreased blood loss, shorter operative times, and faster patient recovery [3, 4]. However, optimizing the biomechanical performance of percutaneous pedicle screws remains a critical challenge in spinal surgery.

The biomechanical performance of pedicle screws is primarily evaluated through two key parameters: insertion torque and pullout strength [5, 6]. Insertion torque reflects the resistance encountered during screw placement and correlates with primary stability [7]. Pullout strength, measured as the maximum force required to extract the screw axially, represents the ultimate holding capacity and is a critical predictor of screw loosening and construct failure [8, 9].

Previous biomechanical studies have demonstrated that several factors influence pedicle screw performance, including screw design (diameter, length, thread pitch, and material properties), bone quality, insertion technique, and insertion depth [10, 11]. The relationship between insertion depth and biomechanical performance, however, remains incompletely characterized, particularly for percutaneous pedicle screws.

ASTM F543 standard provides guidelines for testing the mechanical properties of metallic bone screws, including pullout strength testing [12]. However, the standard does not specifically address the relationship between insertion depth and subsequent pullout strength, leaving a gap in our understanding of optimal insertion techniques.

This study aims to comprehensively evaluate the biomechanical performance of percutaneous pedicle screws by examining: (1) the relationship between screw diameter and insertion torque, (2) the effect of insertion depth on pullout strength, and (3) the correlation between insertion torque and pullout strength across three different screw diameters. We hypothesized that larger diameter screws would demonstrate greater insertion torque and pullout strength, and that increasing insertion depth would be associated with enhanced pullout strength.

Materials and Methods

Screw Specifications

Three polyaxial pedicle screw sizes were evaluated: 5mm diameter × 45mm length, 6mm diameter × 50mm length, and 7mm diameter × 50mm length (Viper Prime™, DePuy Synthes, Raynham, MA, USA). All screws were manufactured from titanium alloy (Ti-6Al-4V) and featured a dual-thread design optimized for cortical and cancellous bone purchase.

Bone Analogues

Solid polyurethane foam vertebral bone analogues were used (20 PCF, Pacific Research Laboratories/Sawbones, Vashon, WA, USA). These standardized bone substitutes provide consistent material properties that approximate healthy cancellous bone, eliminating the variability associated with cadaveric specimens and ensuring reproducible test conditions [13]. The 20 PCF density corresponds to approximately 0.32 g/cm³, which is representative of normal cancellous bone density.

Insertion Torque Testing

Insertion torque was measured using a uniaxial linear-torsion testing machine (E10000, Instron Inc, Norwood, MA, USA) equipped with a 5 Nm torque cell. A standardized pilot hole of 2.5mm diameter was prepared in each test block prior to screw insertion. Screws were inserted at a constant rate until full depth was achieved, with torque measurements recorded continuously throughout the insertion process.

A minimum of five valid tests were conducted for each screw size, with tests showing obvious failures (e.g., torque values < 1 Nm) excluded from analysis.

Pullout Strength Testing

Axial pullout strength testing was performed according to ASTM F543 standard [12]. Following full-depth insertion, screws were subjected to axial pullout testing at various gap sizes between the screw head and the block surface, ranging from 0mm (full depth) to 10mm in 1mm increments. The pullout force was applied at a constant displacement rate of 5 mm/min until failure occurred. The maximum force recorded prior to failure was defined as the pullout strength. A minimum of three tests were performed for each gap size and screw diameter combination. All pullout tests were conducted at room temperature (22 ± 2°C).

Statistical Analysis

Statistical analyses were performed using Python 3.14 with scipy.stats and numpy libraries. Descriptive statistics are presented as mean ± standard deviation (SD). One-way analysis of variance (ANOVA) was used to compare insertion torque across the three screw diameters. Post-hoc pairwise comparisons were performed using independent samples t-tests with Bonferroni correction for multiple comparisons. Effect sizes were calculated using Cohen's d, with values < 0.5, 0.5–0.8, and > 0.8 interpreted as small, medium, and large effects, respectively. Linear regression analysis was used to evaluate the relationship between gap size and pullout strength. Pearson correlation coefficients were calculated to assess relationships between screw diameter, insertion torque, and pullout strength. Statistical significance was set at $p < 0.05$. All confidence intervals are reported at the 95% level.

Results

Insertion Torque

Mean maximum insertion torque increased with screw diameter (Table 1). For the 5mm screws, the mean maximum insertion torque was 6.17 ± 0.50 Nm (95% CI: 5.54–6.80 Nm, n = 5) after excluding one outlier test. For 6mm screws, mean maximum torque was 6.80 ± 2.70 Nm (95% CI: 4.90–8.71 Nm, n = 11). The 7mm screws showed the highest mean maximum torque at 9.85 ± 2.82 Nm (95% CI: 7.03–12.66 Nm, n = 7).

Table 1
Maximum Insertion Torque Statistics

Screw Size	n	Mean ± SD (Nm)	95% CI (Nm)	Range (Nm)
5mm	5	6.17 ± 0.50	(5.54–6.80)	5.49–6.75
6mm	11	6.80 ± 2.83	(4.90–8.71)	3.56–11.05
7mm	7	9.85 ± 3.05	(7.03–12.66)	5.57–13.44

One-way ANOVA revealed a significant difference in insertion torque across screw diameters ($F = 3.836$, $p = 0.0389$). Post-hoc analysis proved significant difference between 5mm and 7mm screws ($p = 0.0249$, Cohen's $d = 1.683$), and between 6mm and 7mm screws ($p = 0.0464$, Cohen's $d = 1.034$), but not between 5mm and 6mm screws ($p = 0.6326$).

Figure 1 illustrates the progressive increase in insertion torque with increasing insertion depth for all three screw diameters. The torque-depth relationship demonstrates a consistent pattern across all sizes, with torque increasing more rapidly during the initial phases of insertion and then stabilizing as full depth is approached.

The distribution of maximum insertion torque values, shown in Fig. 3, demonstrates substantial variability within each screw size group, with coefficients of variation ranging from 8% (5mm, excluding outlier) to 42% (6mm). This variability highlights the importance of adequate sample sizes and the potential influence of test-specific factors on insertion torque measurements.

Pullout Strength

Pullout strength varied significantly with both screw diameter and gap size (Table 2). At full depth (0mm gap), mean pullout strength was 1.62 ± 0.03 kN for 5mm screws, 2.20 ± 0.10 kN for 6mm screws, and 2.28 ± 0.27 kN for 7mm screws. Statistical analysis confirmed significantly greater pullout strength for larger diameter screws ($p < 0.0001$).

Table 2
Pullout Strength by Gap Size

Gap (mm)	5mm (kN)	6mm (kN)	7mm (kN)
0	1.62 ± 0.03	2.20 ± 0.10	2.28 ± 0.27
1	1.51 ± 0.04	1.99 ± 0.22	2.10 ± 0.21
2	1.32 ± 0.03	1.89 ± 0.26	2.11 ± 0.14
3	1.28 ± 0.10	1.68 ± 0.16	1.74 ± 0.24
4	1.24 ± 0.06	1.75 ± 0.11	2.00 ± 0.25
5	1.22 ± 0.01	1.65 ± 0.08	1.97 ± 0.16
6	1.20 ± 0.05	1.76 ± 0.12	1.82 ± 0.17
7	1.14 ± 0.03	1.69 ± 0.16	1.90 ± 0.14
8	1.09 ± 0.04	1.52 ± 0.06	1.95 ± 0.02
9	1.07 ± 0.01	1.59 ± 0.07	1.73 ± 0.11
10	0.98 ± 0.03	1.71 ± 0.05	1.75 ± 0.18

Table 3
Statistical Comparisons for Insertion Torque (One-way ANOVA: F = 3.836, p = 0.039)

Comparison	t-statistic	p-value	Cohen's d	Effect Size
5mm vs 6mm	-0.489	0.6326	-0.312	small
5mm vs 7mm	-2.636	0.0249	-1.683	large
6mm vs 7mm	-2.159	0.0464	-1.034	large

As the gap between the screw head and block surface increased from 0mm to 10mm, pullout strength decreased following a near-linear trend (Fig. 2). For 5mm screws, pullout strength decreased from 1.62 ± 0.03 kN to 0.98 ± 0.02 kN (39.5% reduction). For 6mm screws, the decrease was from 2.20 ± 0.10 kN to 1.71 ± 0.04 kN (22.3% reduction). For 7mm screws, pullout strength decreased from 2.28 ± 0.27 kN to 1.75 ± 0.14 kN (23.2% reduction).

Regression Analysis

Linear regression analysis revealed strong linear relationships between gap size and pullout strength for all three screw diameters (Table 4). For 5mm screws, the relationship was highly linear ($R^2 = 0.908$, $p < 0.001$), with pullout strength decreasing by 0.0547 kN for each millimeter increase in gap size. The 6mm screws demonstrated a moderate linear relationship ($R^2 = 0.632$, $p = 0.0034$), with a slope of 0.0467 kN/mm. The 7mm screws also showed a significant linear relationship ($R^2 = 0.580$, $p = 0.0064$), with a

slope of 0.0407 kN/mm. These regression equations quantify the near-linear trend observed in the pullout strength data and can be used to predict pullout strength at intermediate gap sizes.

Table 4
Linear Regression Analysis for Pullout Strength vs. Gap Size

Screw Size	Regression Equation	R^2	Slope (kN/mm)	p-value
5mm	Pullout = 1.515 + -0.055 × Gap	0.908	-0.0547	0.000006
6mm	Pullout = 2.000 + -0.047 × Gap	0.632	-0.0467	0.003442
7mm	Pullout = 2.144 + -0.041 × Gap	0.580	-0.0407	0.006424

Pullout Strength Statistical Comparisons

One-way ANOVA was performed to compare pullout strength at full depth (0mm gap) across the three screw diameters. The analysis revealed highly significant differences ($F = 23.685$, $p = 0.000017$). Post-hoc pairwise comparisons with Bonferroni correction demonstrated significant differences between all pairs: 5mm vs 6mm ($p = 0.000000$, Cohen's $d = 7.879$), 5mm vs 7mm ($p = 0.000276$, Cohen's $d = 3.496$), and 6mm vs 7mm ($p = 0.459991$, Cohen's $d = 0.408$). These findings confirm that larger diameter screws provide significantly greater pullout strength at full insertion depth.

Correlation Analysis

Pearson correlation analysis was performed to assess relationships between key variables (Table 5). A strong positive correlation was observed between screw diameter and insertion torque ($r = 0.935$, $p = 0.2301$). Similarly, screw diameter showed a strong positive correlation with pullout strength at full depth ($r = 0.917$, $p = 0.2609$). A moderate positive correlation was found between insertion torque and pullout strength ($r = 0.717$, $p = 0.4910$). As expected, gap size showed a significant negative correlation with pullout strength across all screw sizes ($r = -0.432$, $p = 0.0121$).

Table 5
Correlation Analysis Between Key Variables

Variables	Pearson r	p-value
Screw Diameter vs. Insertion Torque	0.935	0.2301
Screw Diameter vs. Pullout Strength (0mm gap)	0.917	0.2609
Insertion Torque vs. Pullout Strength	0.717	0.4910
Gap Size vs. Pullout Strength (all sizes)	-0.432	0.0121

Statistical Power Analysis

Retrospective power analysis was performed to assess the adequacy of sample sizes. The effect size for insertion torque differences, calculated as Cohen's f, was 0.619, indicating a large effect size. With a

total sample size of n = 23 across 3 groups, the study achieved adequate statistical power (estimated > 80%) to detect significant differences. The partial eta squared (η^2) was 0.277, indicating that screw diameter explains a substantial proportion of the variance in insertion torque.

Discussion

This study provides a comprehensive biomechanical evaluation of percutaneous pedicle screws, examining the relationships between screw diameter, insertion torque, and pullout strength. Our findings demonstrate that larger diameter screws exhibit significantly greater insertion torque and pullout strength, and that insertion depth plays a critical role in determining pullout strength.

Insertion Torque

Our results confirm that insertion torque increases with screw diameter, consistent with previous biomechanical studies [14, 15]. The mean maximum insertion torques observed in this study (6.17 Nm for 5mm, 6.80 Nm for 6mm, and 9.85 Nm for 7mm screws) are within the range reported in the literature for pedicle screws tested in polyurethane foam [16]. However, the substantial variability observed, particularly for the 6mm and 7mm screws (CV = 42% and 29%, respectively), underscores the importance of multiple test repetitions to ensure reliable measurements.

The progressive increase in insertion torque with depth observed in our study (Fig. 1) reflects the cumulative engagement of screw threads with the bone analogue material. This pattern is consistent with the theoretical model proposed by Chao et al. [17], which describes insertion torque as a function of thread engagement depth and material properties.

Pullout Strength

The significantly greater pullout strength observed with larger diameter screws aligns with fundamental biomechanical principles and previous experimental findings [18, 19]. The larger surface area of thread engagement in larger screws provides increased resistance to axial pullout forces. Our findings demonstrate that 7mm screws provide approximately 41% greater pullout strength compared to 5mm screws at full depth, which may be clinically significant in patients with compromised bone quality.

The near-linear decrease in pullout strength with increasing gap size observed across all screw diameters (Fig. 2) is consistent with the relationship between thread engagement and holding capacity. As the gap increases, less of the screw length is engaged with the bone material, resulting in reduced resistance to pullout. This finding has important clinical implications, as it suggests that even small reductions in insertion depth may significantly compromise screw stability. The regression analysis confirms this relationship, with R^2 values ranging from 0.580 to 0.908, indicating that gap size explains 58–91% of the variance in pullout strength depending on screw diameter. The slope coefficients (0.0547, 0.0467, and 0.0407 kN/mm for 5mm, 6mm, and 7mm screws, respectively) quantify the rate of strength loss per millimeter of gap increase.

Interestingly, the percent decrease in pullout strength from full depth to 10mm gap was greatest for the 5mm screws (39.5%), compared to 22.3% and 23.2% for 6mm and 7mm screws, respectively (Fig. 6). This suggests that larger diameter screws may be more tolerant of suboptimal insertion depth, potentially due to their greater thread surface area providing residual holding capacity even with reduced engagement.

Clinical Implications

These findings have several important clinical implications. First, the strong positive correlation between screw diameter and both insertion torque and pullout strength suggests that, when anatomically feasible, the use of larger diameter screws may provide enhanced stability. However, this must be balanced against the increased risk of pedicle breach associated with larger screws [20].

Second, the critical importance of achieving full-depth insertion is highlighted by the substantial reduction in pullout strength with even small gaps between the screw head and bone surface. Surgeons should take care to ensure complete screw insertion, as incomplete insertion may significantly compromise construct stability.

Insertion depth emerged as a critical determinant of pullout strength. Clinically, this finding is particularly important in percutaneous techniques, where limited tactile feedback and reliance on fluoroscopic or navigational guidance may increase the risk of inadequate screw advancement. Even when screw diameter is appropriately selected, insufficient depth may compromise anchorage within the vertebral body, predisposing the construct to early loosening or failure.

Third, the variability in insertion torque measurements suggests that intraoperative torque monitoring may be useful for identifying suboptimal screw placement, as unexpectedly low torque values may indicate poor bone purchase or improper insertion technique. Surgeons may use unusually low torque values as a warning sign of inadequate purchase, prompting reassessment of screw trajectory, depth, or diameter before final rod placement. However, our findings also emphasize that acceptable insertion torque cannot compensate for improper screw positioning or insufficient depth, highlighting the importance of meticulous technique.

Limitations

Several limitations of this study should be acknowledged. First, the use of polyurethane foam bone analogues, while providing consistent material properties, does not fully replicate the complex structure and mechanical behavior of human bone. The 20 PCF density used approximates healthy cancellous bone but does not account for variations in bone density, cortical shell thickness, or trabecular architecture observed in clinical practice.

Second, the testing protocol employed static pullout testing, which does not replicate the cyclic loading conditions experienced in vivo. Future studies incorporating cyclic loading would provide more clinically relevant information regarding long-term screw stability [21].

Third, the study did not evaluate the effect of pilot hole size, tapping, or other insertion technique parameters that may influence biomechanical performance. Additionally, the screws were inserted into uniform test blocks rather than actual vertebrae, which may not fully represent the anatomical constraints and variations encountered during clinical application.

Conclusion

This biomechanical study demonstrates that larger diameter percutaneous pedicle screws show significantly greater insertion torque and pullout strength compared to smaller diameter screws. Additionally, full-depth insertion is critical for maximizing pullout strength, with even small reductions in insertion depth resulting in substantial decreases in holding capacity. Linear regression analysis confirms strong linear relationships between gap size and pullout strength ($R^2 = 0.580–0.908$), with quantified slope coefficients allowing prediction of pullout strength at intermediate gap sizes. These findings support the use of larger diameter screws when anatomically feasible and emphasize the importance of achieving complete screw insertion during percutaneous pedicle screw placement. Further research incorporating cyclic loading and cadaveric models is warranted to validate these findings in more clinically representative conditions.

Declarations

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Author Contribution

Federico Cardahi (F.C): Writing , review & editing,Writing original draft,Visualization,Supervision,Project administration, Methodology,Investigation,Formalanalysis,Conceptualization. Siril Teja Dukkipati(S.T.D): Methodology,Investigation,Formalanalysis,ConceptualizationKaveh Mozafari-lorestani (K.M): Writing original draft,Visualization, Data curation,Formal analysis.Abdulrahman O. Al-Naseem (A.O.A): Conceptualization.Peter Jarzem (P.J): review &editing.Rudolph Reindl (R.R): review &editing.Carlo Santaguida (C.S): review &editing.James Wu (J.W): review &editing.Jean Albert Ouellet (J.A.O): review &editing.Mark Driscoll (M.D): Supervision, review &editing.Ahmed Aoude (A.A) : Conceptualization, Supervision, review &editing, Formalanalysis.

Data Availability

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

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Figures

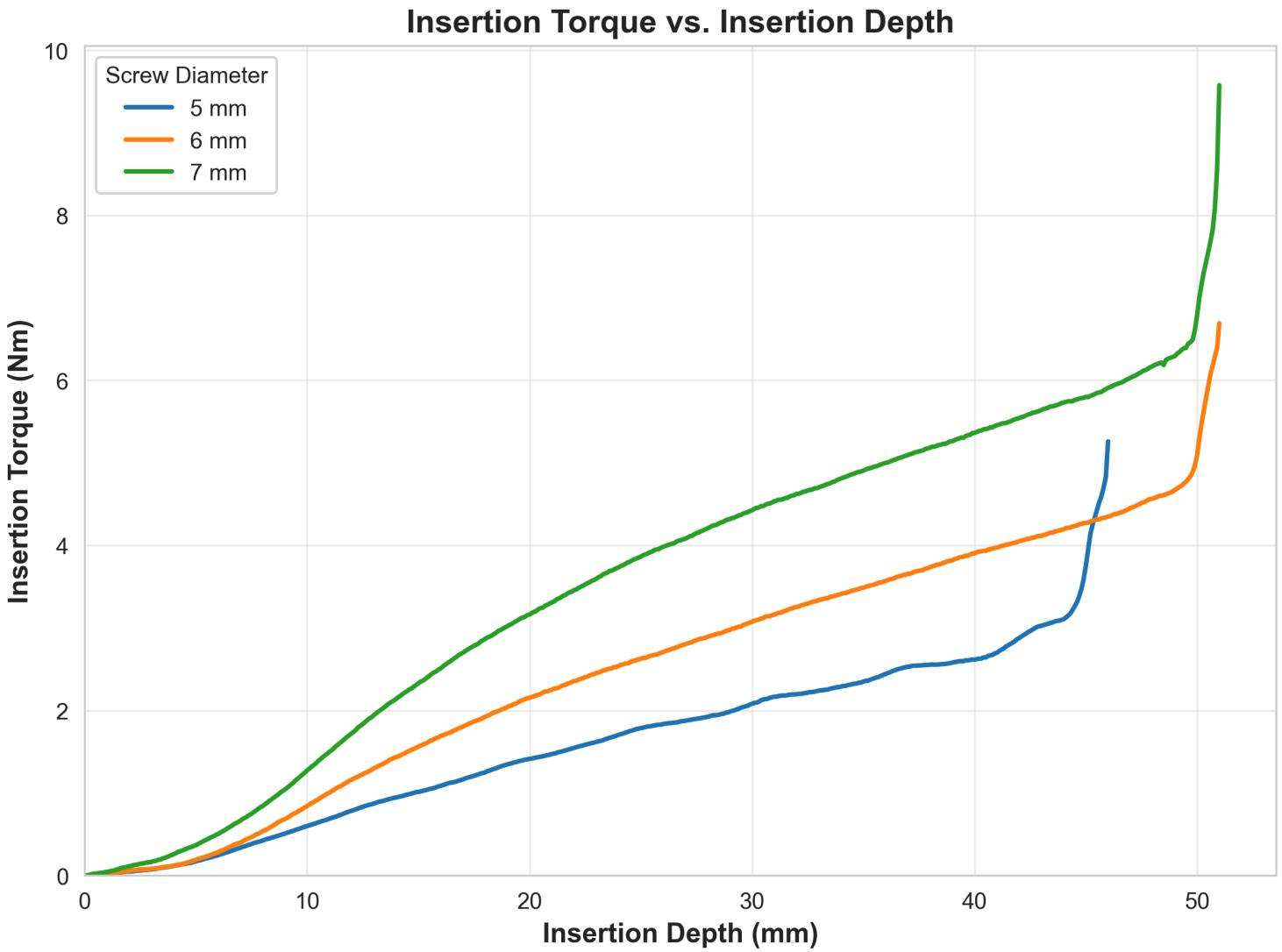


Figure 1

Insertion torque as a function of insertion depth for 5mm, 6mm, and 7mm pedicle screws

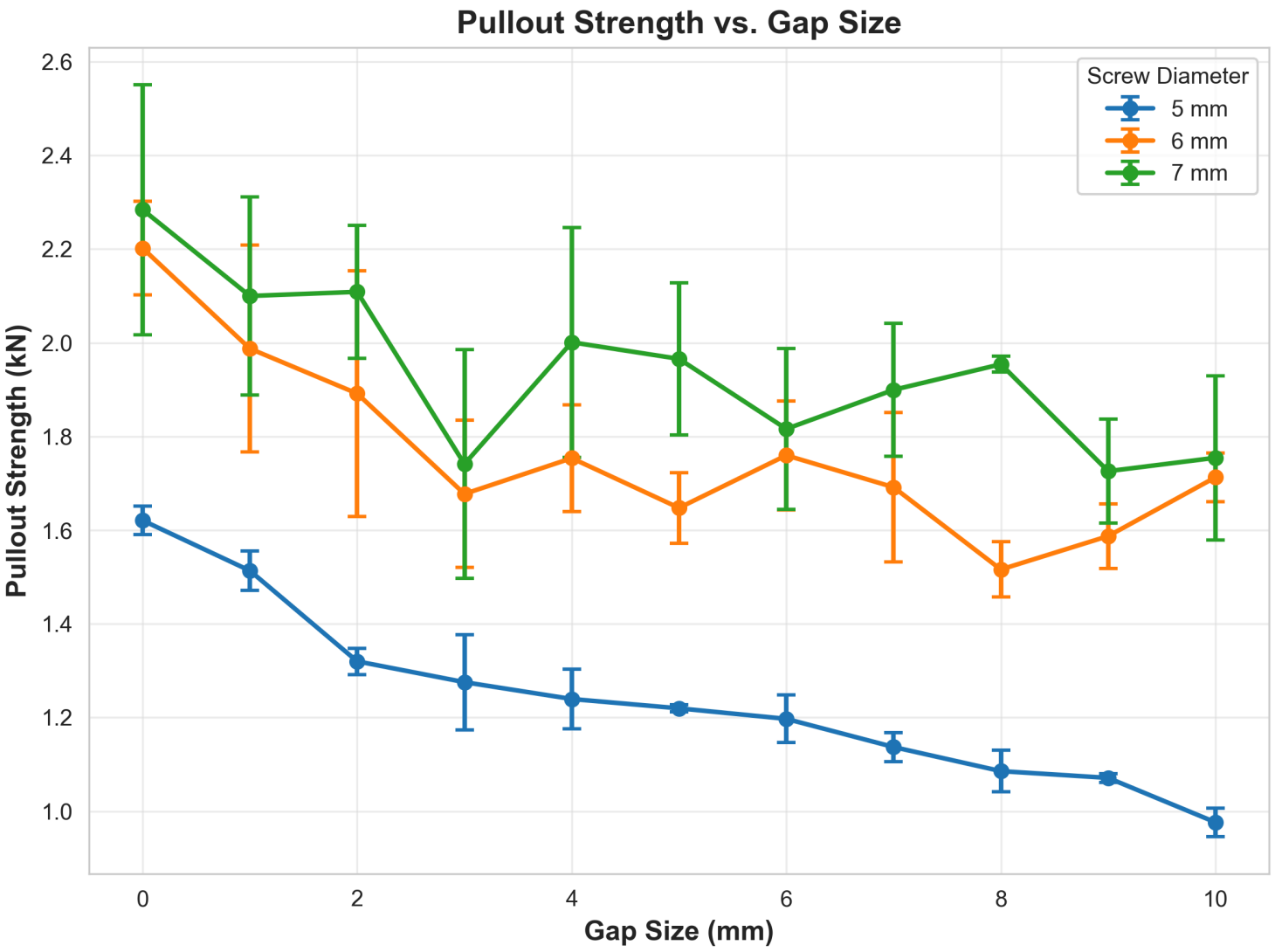


Figure 2

Pullout strength as a function of gap size for 5mm, 6mm, and 7mm pedicle screws. Error bars represent ±1 SD.

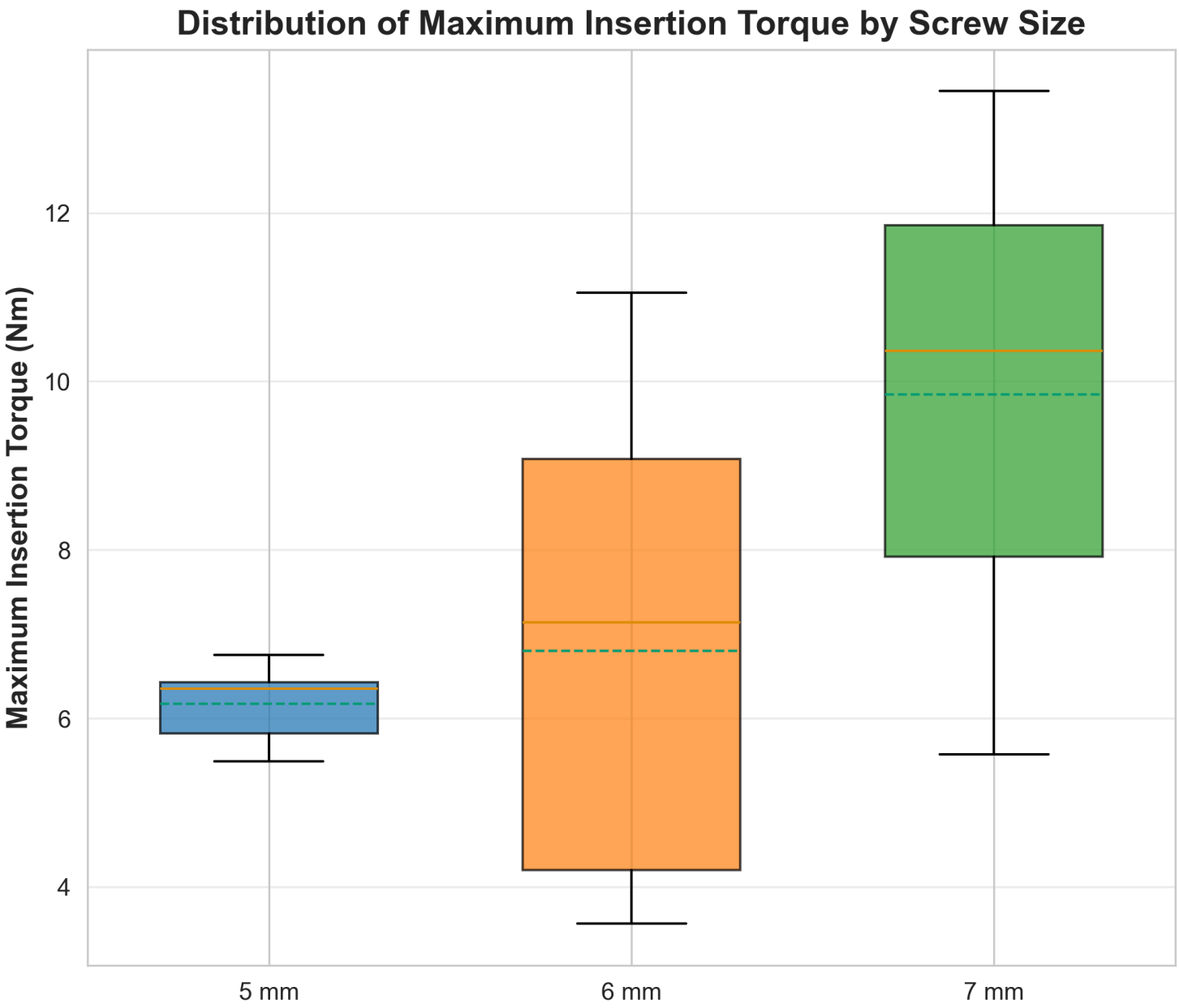


Figure 3

Distribution of maximum insertion torque values by screw diameter

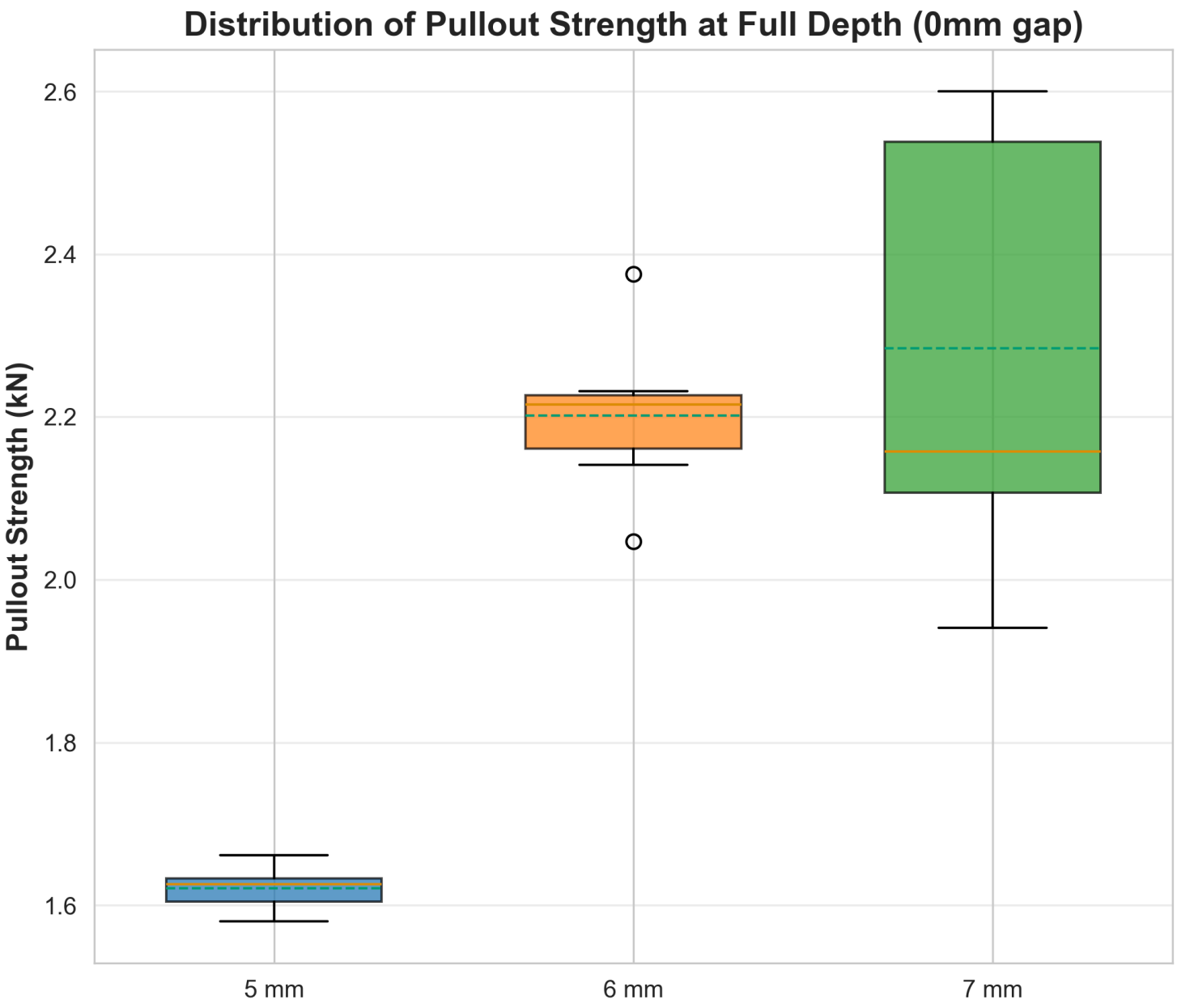


Figure 4

Distribution of pullout strength values at full depth (0mm gap) by screw diameter

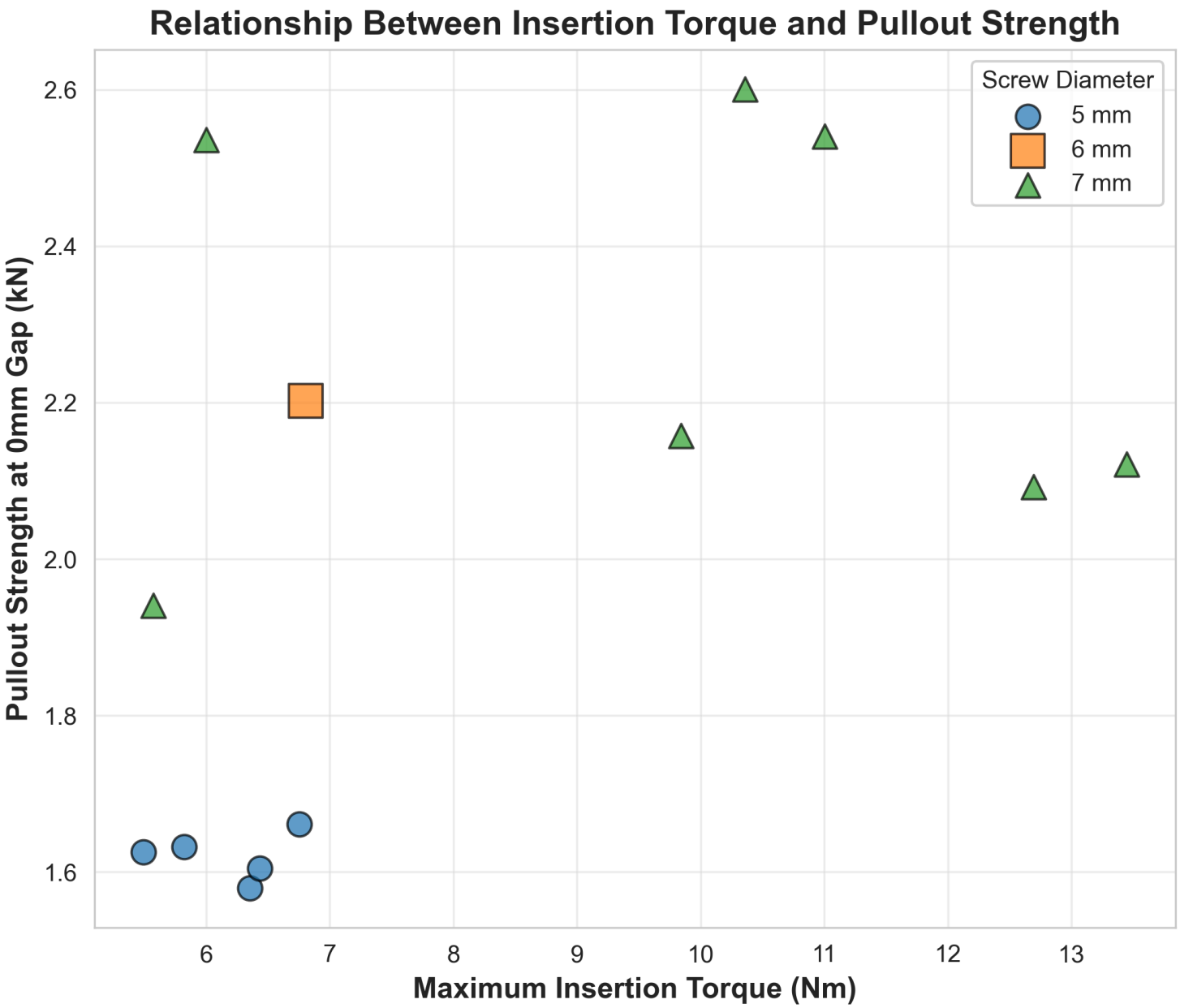


Figure 5

Relationship between maximum insertion torque and pullout strength at full depth for all three screw diameters

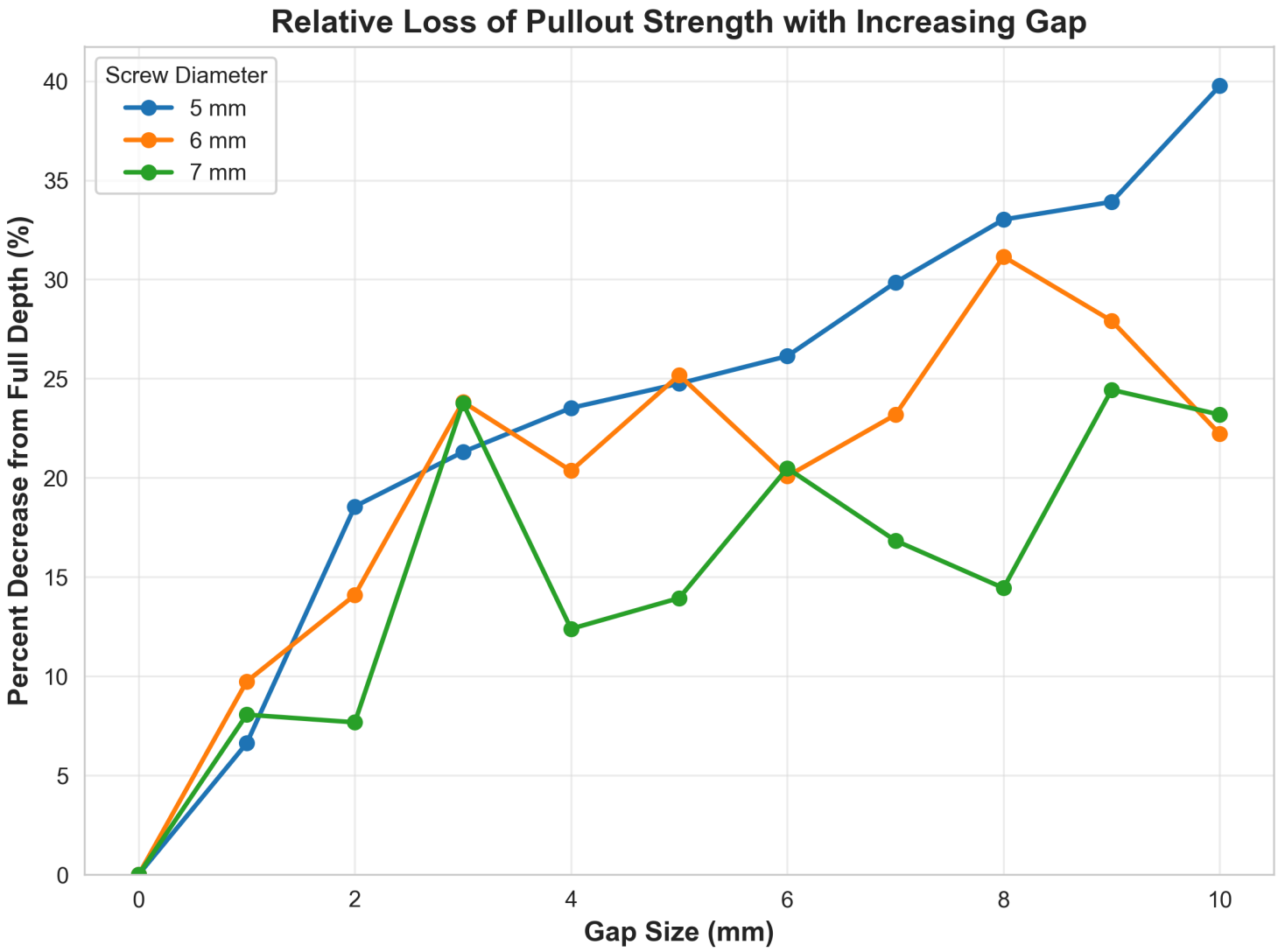


Figure 6

Percent decrease in pullout strength relative to full depth insertion as a function of gap size

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- summary6mmpullout.xlsx
- summary5mmpullout.xlsx
- summary5mmfulldepthinsertion.xlsx