

Article

Measurement of Fastening Torque of Rod Securing Spinal Implant Screws

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Abstract

Background/Objectives: The mechanical performance of spinal instrumentation depends on appropriate fixation of rod-securing screws. Although manufacturer-recommended torque values and torque-limiting instruments are widely used in spinal surgery, the contribution of surgeon-related factors to manually applied tightening torque remains insufficiently characterized. This study aimed to quantify the magnitude and variability of tightening torque applied by spine surgeons and to investigate the influence of handling technique and surgeon orientation on torque generation. **Methods:** A thoracolumbar spine model instrumented with pedicle screw–rod constructs was used in an experimental setup. Twenty-two spine surgeons from six institutions performed a total of 220 screw-tightening procedures using a standardized manual screwdriver setup. Tightening torque was estimated from measured loosening torque using a previously established calibration relationship. Hand usage, hand position, and surgeon orientation relative to the construct were recorded. Statistical analyses were performed to compare torque values between different handling conditions. **Results:** The mean estimated tightening torque was 4.52 Nm, with considerable inter-individual variability among surgeons. Two-handed grip produced significantly ($p = 0.006$) higher torque (5.76 ± 1.46 Nm) compared to thumb-downward (3.47 ± 1.19 Nm). Among the univariate linear regression analyses, only the two-handed grip technique showed a significant association with higher fastening torque (B [95% CI]: 1.88 [0.56; 3.21], $p = 0.008$). The other factors (age, height, weight, experience) did not show a significant relationship. **Conclusions:** Manual tightening torque during spinal instrumentation shows substantial variability among surgeons and is influenced by handling technique and surgeon position. These findings demonstrate the importance of considering human factors in biomechanical evaluations of spinal fixation procedures. Further studies are required to determine the clinical significance of this variability.



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Keywords: fastening torque; spinal instrumentation; pedicle screw; biomechanics; torque variability; surgical technique; human factors

1. Introduction

Spinal instrumentation systems commonly rely on rod–screw constructs to achieve mechanical stability and maintain spinal alignment. The integrity of these constructs critically depends on the secure fixation of individual components, particularly the tightening of set screws that lock the rods within pedicle screw heads. Insufficient or excessive tightening

may affect the mechanical behavior of the construct and may compromise the intended fixation performance of the implant system.

To ensure the reliability and safety of spinal implants, several standardized testing protocols have been established. Widely used standards [1,2] define methodologies for evaluating the mechanical behavior of spinal implant constructs, including static and fatigue performance as well as the properties of interconnection mechanisms. Although these standards provide a robust framework for assessing structural integrity under controlled laboratory conditions, they do not address the variability associated with torque application during surgical procedures.

While international guidelines and modern spinal instrumentation platforms advocate for the use of calibrated torque-limiting screwdrivers, substantial heterogeneity exists in real-world clinical practice. In many healthcare systems, regional surgical departments, and resource-limited settings, dedicated torque-limiting instruments are not universally available or routinely utilized for every procedure. In such environments, set-screw tightening relies entirely on the surgeon's subjective tactile sensation and manual force control. This clinical reality is also reflected in our multi-institutional cohort, where routine torque-limiting instrument utilization varied across participating centers.

Despite extensive biomechanical investigations focusing on implant design, fixation strength, and load distribution [3–15], relatively little attention has been given to the actual torque applied during manual spinal instrumentation and its variability among surgeons. Furthermore, the influence of fundamental ergonomic and handling factors—such as hand positioning, the number of hands used (grip technique), and surgeon orientation relative to the implant—on manual torque generation remains poorly understood. Rather than evaluating the clinical failure rate of a specific proprietary implant system, establishing the baseline variability of manual torque application addresses a critical and underreported gap in surgical biomechanics.

The aim of the present study was therefore to quantify the magnitude and variability of tightening torque applied by spine surgeons using a standardized experimental setup, and to evaluate the effect of handling technique and surgeon positioning on manual torque generation.

2. Materials and Methods

2.1. Study Design and Model

A realistic synthetic composite spine model including all thoracic and lumbar vertebrae, intervertebral discs, and the sacrum (Biocalderoni, Budapest, Hungary) was used for the experimental setup. Standardized synthetic phantoms manufactured from rigid polyvinyl chloride (PVC) and thermoplastic polymers (elastic modulus $E \approx 2.5\text{--}3.5$ GPa) are widely accepted in orthopedic biomechanical testing to eliminate confounding variables associated with inter-donor bone mineral density (BMD) variability and bone thread shear failure during repetitive testing, thereby providing a reproducible baseline to isolate surgeon motor performance. The model was mounted on a portable platform at a height corresponding to standard posterior spinal surgical positioning. Bilateral pedicle tulip-headed screws were inserted into all lumbar vertebrae. To allow repeated non-destructive measurements during the experimental procedures, a custom-designed modification of the screw head interface was developed: the original set screw interface was modified by integrating a high-strength internally threaded nut into the tulip head, allowing fixation with a high-tensile screw component (Figure 1).

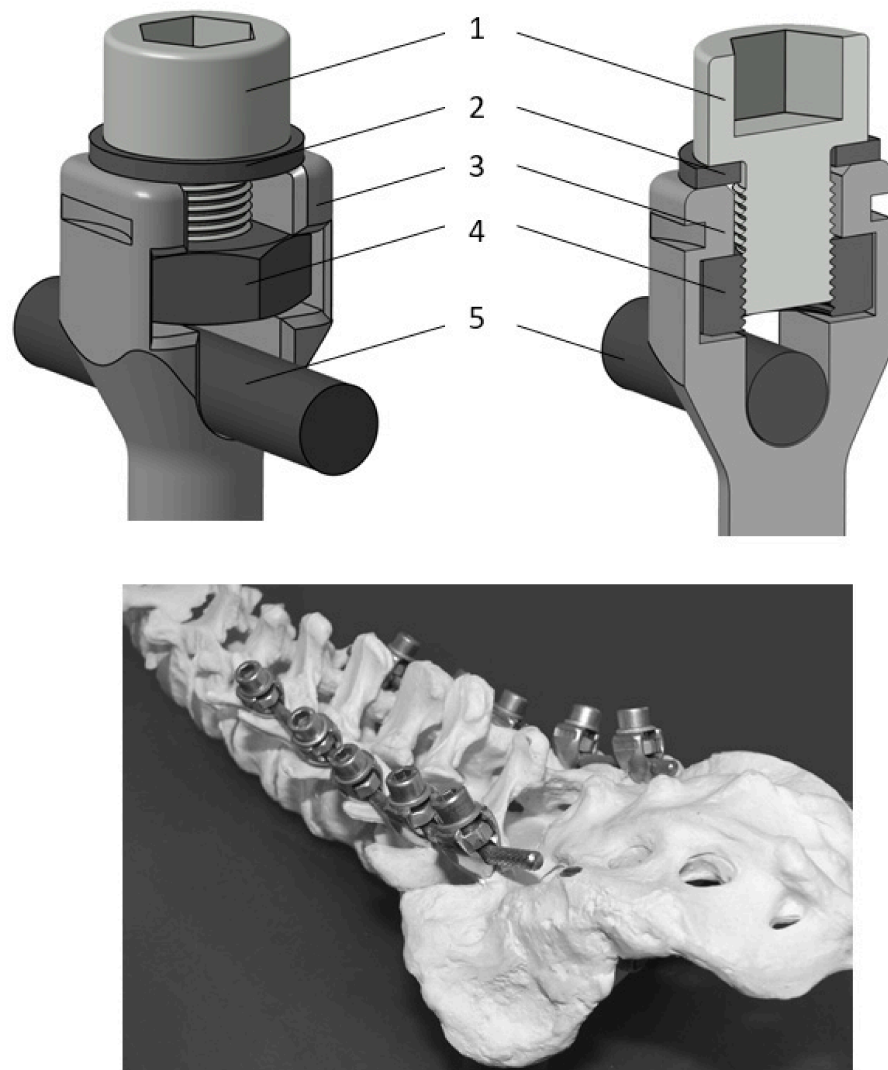


Figure 1. Schematic representation of the modified screw and measurement apparatus. (1) High-tensile screw, (2) washer, (3) modified pedicle screw, (4) high-tensile nut, (5) rod.

The measurement apparatus consisted of three components:

1. Standard surgical screwdriver (geometrically identical to instruments used in operating theaters)
2. Calibrated torque-limiting screwdriver (Torqueleader Quickset, Guildford, UK) for calibration
3. Calibrated dial-type torque wrench (WERA 7112BDS, Wuppertal, Germany) for loosening torque measurement

2.2. Calibration Phase (First Measurement Series)

To estimate the applied tightening torque from measured loosening torque values, a calibration procedure was performed before the surgeon assessment phase. All ten screw positions used in the experimental setup were calibrated individually.

For each screw, an initial tightening–loosening cycle was performed to allow mechanical settling of the screw connection. This preliminary cycle was not included in the calibration calculations.

Subsequently, two complete calibration series were performed at predefined tightening torque levels ranging from 2.0 to 6.0 Nm in 0.5 Nm increments (2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, and 6.0 Nm). The predefined tightening torque values were applied using a calibrated

torque-controlled screwdriver, and the corresponding loosening torque was measured using a calibrated analog torque wrench.

For each screw position and each calibration point, the loosening-to-tightening torque ratio was calculated by dividing the measured loosening torque by the applied tightening torque. The final screw-specific loosening-to-tightening torque ratio was determined by averaging the ratios obtained from the two calibration series.

During the surgeon assessment phase, the measured loosening torque values were converted into estimated tightening torque values using the corresponding screw-specific loosening-to-tightening torque ratios.

2.3. Surgeon Assessment Phase (Second Measurement Series)

Twenty-two spine surgeons from six Hungarian institutions participated in the experimental assessment. Individual surgeon ($n = 22$) characteristics are presented in Table 1. Substantial inter-surgeon variability was observed, with individual mean torques ranging from 1.9 Nm to 7.4 Nm (overall mean $\pm$ SD: 4.52 ± 1.84 Nm).

Table 1. Characteristics of surgeons.

Surgeons ($n = 22$)	Mean $\pm$ SD/N (%)
Gender: male	22 (100%)
Age (years)	45.50 ± 8.56
Height (cm)	176.91 ± 6.45
Weight (kg)	81.73 ± 5.81
Experience in spinal surgery (years)	18.64 ± 8.35
Torque-meter used in daily routine	17 (77.3%)
Grip Technique	
thumb downwards	10 (45.5%)
thumb upwards	5 (22.7%)
with two hands	7 (31.8%)

SD—standard deviation; n —number.

Each surgeon performed tightening procedures on all 10 set screw connections of the lumbar construct using their habitual surgical technique. Therefore, a total of 220 tightening procedures were recorded (22 surgeons $\times$ 10 screws), consisting of 110 right-sided and 110 left-sided screw-tightening procedures.

Participants were instructed to perform the tightening maneuver according to their usual surgical practice. No predefined grip technique or tightening sequence was imposed. Each surgeon selected their preferred order of screw tightening and used their habitual hand positioning during the procedure. Surgeons indicated their preferred grip technique, which was documented by the observer.

The following parameters were recorded for each tightening maneuver by an independent observer:

- Grip technique (thumb upwards, thumb downwards, or with two hands)
- Hand dominance (right or left)
- Standing position relative to the model (right or left side)
- Routine use of torque-limiting or torque-controlled instruments at the participant's institution

Measurement Protocol:

1. The spine model was secured horizontally at surgical height, and the set screws were loosened before each measurement to standardize the starting condition

2. Surgeons tightened the set screws in the model using the same manual screwdriver for all measurements (Figure 2)
3. Loosening torque was measured using a calibrated torque wrench, and the maximum torque value was recorded. The applied tightening torque was estimated from the measured loosening torque using a previously established calibration relationship
4. All data were recorded in standardized measurement protocols



Figure 2. The three different grip techniques (thumb-upward, thumb-downward, two-handed).

2.4. Control Phase (Third Measurement Series)

To evaluate whether repeated use during the surgeon assessment phase influenced the mechanical behavior of the screw–screwdriver interface, the calibration procedure described in the first measurement series was repeated after completion of all surgeon measurements.

The tightening–loosening torque ratios obtained before and after the surgeon assessment phase were compared to identify any relevant changes in the screw interface characteristics.

2.5. Calibration Analysis

Prior to the experimental measurements, a calibration procedure was performed to establish the relationship between loosening torque and the corresponding tightening torque. Calibration measurements were performed in three independent repetitions at nine predefined reference tightening torque levels ranging from 2.0 to 6.0 Nm in 0.5-Nm increments. Measurements were obtained at each of the ten screw positions (five on the left and five on the right), resulting in 27 calibration observations per screw position and 270 observations in total.

Position-specific linear regression models were used to establish the calibration equations, with reference tightening torque as the dependent variable and measured loosening torque as the independent variable. A strong linear relationship was observed at all ten screw positions (all $p < 0.001$), with coefficients of determination (R^2) ranging from 0.866 to 0.977. Regression slopes ranged from 1.423 to 1.900 and intercepts from -0.700 to 0.274 Nm. The resulting position-specific regression equations were used to estimate tightening torque from the measured loosening torque (Table 2).

The agreement between estimated and reference tightening torque was further assessed using Bland–Altman analysis. The mean bias was 0.00 Nm, with 95% limits of agreement from -0.60 to 0.60 Nm. Regression of the differences between estimated and reference torque against their mean indicated a small proportional bias ($B = -0.029$, 95% CI: -0.057 to 0.001 , $p = 0.050$), although the explained variance was minimal ($R^2 = 0.014$).

To assess the variability of the calibration procedure across screw positions, the calibration ratio was calculated as the measured loosening torque divided by the corresponding reference tightening torque. The mean calibration ratio across the ten screw positions was 0.649 . The coefficient of variation across the ten position-specific mean calibration ratios

was 5.03%, while the within-position coefficients of variation ranged from 6.68% to 16.09% (Table 3).

Table 2. Position-specific linear regression parameters for estimating tightening torque from measured loosening torque.

Screw Position	R ²	Slope	Intercept	p-Value
Left 1	0.939	1.511	−0.025	<0.001
Left 2	0.929	1.900	−0.700	<0.001
Left 3	0.954	1.476	0.084	<0.001
Left 4	0.945	1.423	0.006	<0.001
Left 5	0.964	1.678	−0.191	<0.001
Right 1	0.955	1.576	0.274	<0.001
Right 2	0.977	1.759	−0.579	<0.001
Right 3	0.969	1.675	−0.395	<0.001
Right 4	0.866	1.498	0.147	<0.001
Right 5	0.950	1.587	0.085	<0.001

Table 3. Calibration ratios and coefficients of variation across the ten screw positions.

Screw Position	Mean Calibration Ratio	SD	CV (%)
Left 1	0.671	0.057	8.48
Left 2	0.637	0.102	16.09
Left 3	0.665	0.054	8.15
Left 4	0.706	0.051	7.18
Left 5	0.631	0.042	6.68
Right 1	0.588	0.051	8.68
Right 2	0.662	0.045	6.8
Right 3	0.666	0.054	8.05
Right 4	0.649	0.073	11.3
Right 5	0.618	0.048	7.83
Across screw positions	0.649	0.033	5.03

SD—standard deviation; CV—coefficient of variation.

2.6. Statistical Analysis

The data distribution was tested using the Shapiro–Wilk test.

Each surgeon performed 10 screw-tightening procedures, comprising five screw positions on both the left and right sides. To account for the repeated measurements within individual surgeons, fastening torque measurements were analyzed using a mixed-effects model (REML). Side (left vs. right) and screw position (positions 1–5) were included as within-subject factors, while grip technique (thumb downwards, thumb upwards, and two-handed) was included as a between-subject factor. The main effects of side, screw position, and grip technique, as well as their interactions, were evaluated. Where appropriate, Sidak post hoc tests were performed with adjustment for multiple comparisons.

For subsequent surgeon-level analyses, the mean fastening torque was calculated from the repeated measurements of each surgeon. Thus, each surgeon contributed one mean fastening torque value, and the unit of analysis in these analyses was the individual surgeon (N = 22). The mean fastening torque was compared between surgeons with and without previous experience using a torque meter using an unpaired *t*-test with Welch's correction. Univariate and multivariate linear regression models were used to determine the influencing factors of fastening torque (Nm). The factors used in the models were the following: age (years), height (cm), weight (kg) of the surgeon, experience in spinal surgery (years), grip technique and experience with torque meter. These regression analyses were

performed using the surgeon-specific mean fastening torque as the dependent variable ($N = 22$).

The significance level was $p < 0.05$ in all cases. All statistical analyses were performed using IBM SPSS Statistics for Windows, version 25.0 (IBM Corp., Armonk, NY, USA).

3. Results

Individual surgeon results and institutional averages are presented in Figures 3 and 4. Substantial inter-surgeon variability was observed, with individual mean torques ranging from 1.9 Nm to 7.4 Nm (overall mean: 4.52 Nm, SD: 1.84 Nm). Institutional averages showed somewhat less variability than individual values.

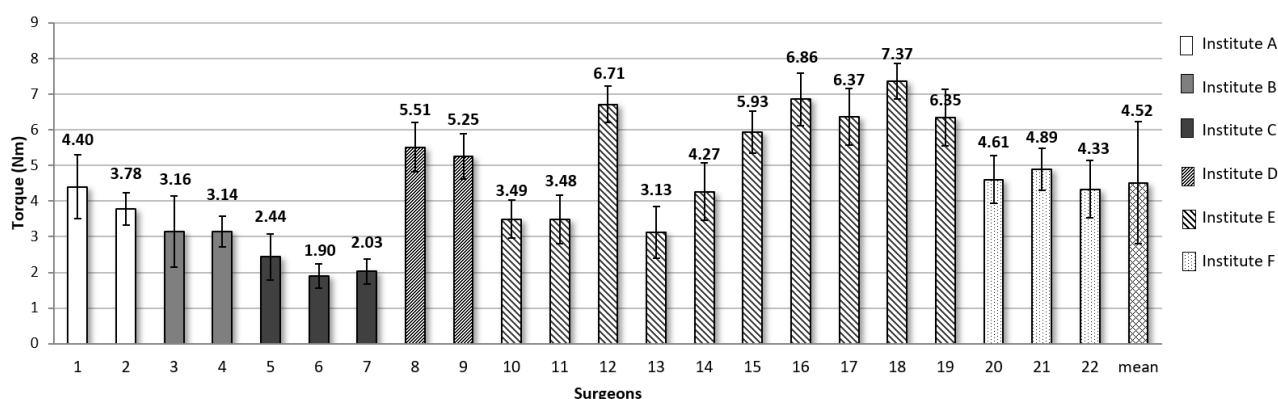


Figure 3. Mean fastening torque values by individual surgeon ($n = 22$). Error bars represent standard deviation.

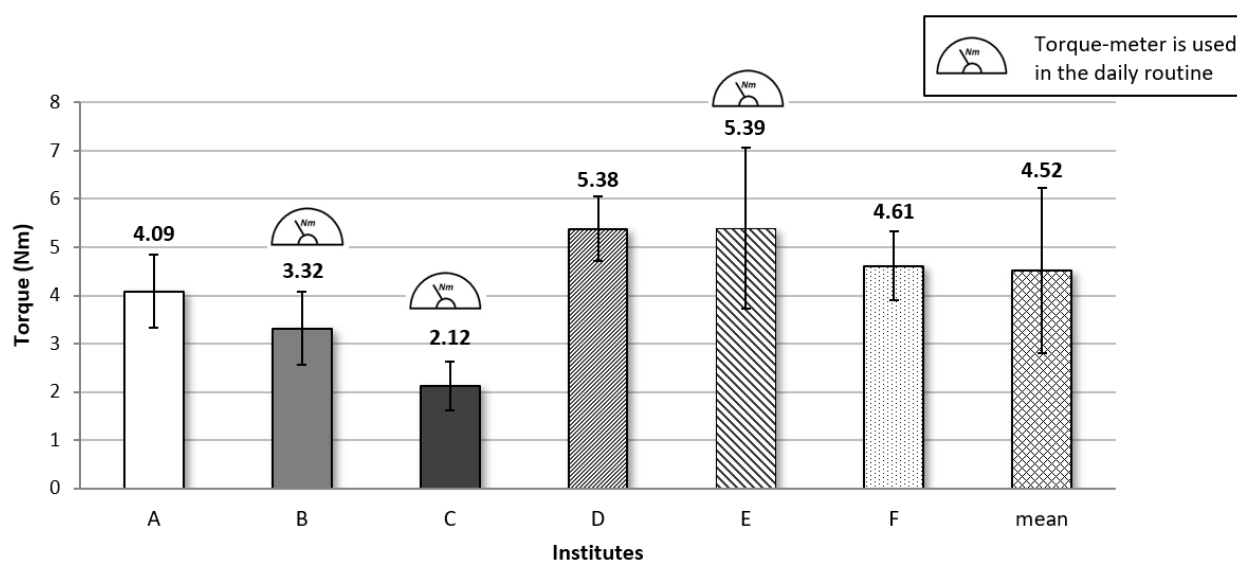


Figure 4. Mean fastening torque values by institution ($n = 6$). Error bars represent standard deviation.

The control calibration series revealed no significant differences in tightening–loosening ratios between pre- and post-assessment measurements ($p = 0.412$), confirming that screw wear did not significantly influence results.

3.1. Grip Technique Effects

A mixed-effects model with repeated measures was used to evaluate the effects of screw position, side, and grip technique on fastening torque while accounting for repeated measurements within individual surgeons. Neither screw position ($p = 0.099$) nor side ($p = 0.178$) had a statistically significant effect on fastening torque. In contrast, fastening

torque differed significantly according to grip technique ($p = 0.001$), which is most evident between the thumb-downwards and two-handed techniques.

The mean tightening torque values for each tightening technique were 5.76 ± 1.46 Nm when using both hands, 3.47 ± 1.19 Nm when using the thumb downward, and 4.7 ± 1.39 Nm when using the thumb upward (Figure 5).

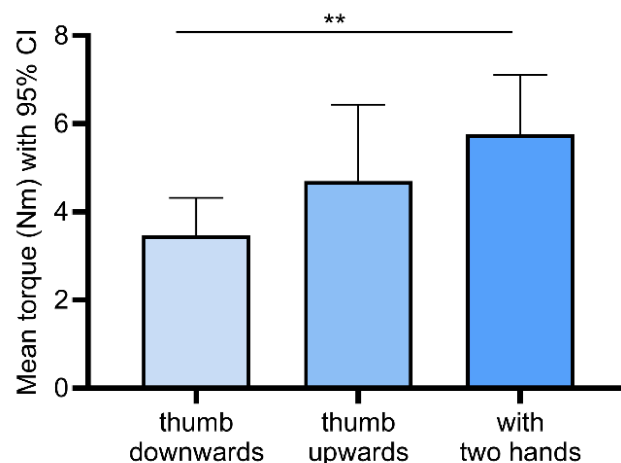


Figure 5. Mean fastening torque values by grip technique (N = 22). ** $p < 0.01$; 95% CI—95% confidence interval.

3.2. Hand Dominance

Only one left-handed surgeon participated, precluding meaningful statistical analysis of handedness effects.

3.3. Torque-Measuring Instrument Use

No significant difference ($p = 0.508$) was found in the applied torque between those who used a torque-meter (4.55 ± 1.84 Nm) and those who did not (4.22 ± 0.49 Nm).

3.4. Univariate and Multivariate Linear Regression Analyses to Determine the Influencing Factors of Fastening Torque

Using the surgeon-specific mean fastening torque as the dependent variable (N = 22), the univariate linear regression analyses showed that only the two-handed grip technique had a significant association with higher fastening torque (B [95% CI]: 1.88 [0.56; 3.21], $p = 0.008$). The other factors did not show a significant relationship (Table 4).

Table 4. Univariate and multivariate linear regression analyses to determine the influencing factors of fastening torque (Nm).

Variables	Univariate Linear Regression Models				Multivariate Linear Regression Model			
	B	β	[95% CI]	<i>p</i> -Value	B	β	[95% CI]	<i>p</i> -Value
Age (years) of surgeon	−0.01	−0.06	[−0.10; 0.08]	0.791	−0.42	−2.21	[−1.17; 0.33]	0.250
Height (cm) of surgeon	−0.04	−0.15	[−0.15; 0.08]	0.518	−0.07	−0.28	[−0.18; 0.04]	0.192
Weight (kg) of surgeon	0.01	0.02	[−0.14; 0.13]	0.943	0.06	0.21	[−0.07; 0.19]	0.324
Experience in spinal surgery (years)	0.01	0.03	[−0.10; 0.08]	0.889	0.45	2.30	[−0.31; 1.20]	0.225
Grip technique	1.88	2.96	[0.56; 3.21]	0.008	2.37	0.70	[0.73; 4.01]	0.008
Experience with torque meter	0.34	0.09	[−1.42; 2.09]	0.695	0.40	0.17	[−1.32; 1.03]	0.427

Significant results are highlighted in bold. 95% CI = 95% confidence interval of B. Grip technique: 0—one-handed, 1—two-handed; Experience with torque-meter: 0—no, 1—yes.

In the multivariate regression model, the two-handed grip remained a significant positive correlate of fastening torque (B [95% CI]: 2.37 [0.73; 4.01], $p = 0.008$) (Table 4).

However, the whole model was not statistically significant ($F = 2.187$, $p = 0.103$, adjusted $R^2 = 0.253$). Given the limited number of surgeons relative to the number of predictors, these multivariable findings should be considered exploratory.

4. Discussion

This study demonstrates substantial variability in screw fastening torque among spine surgeons, with individual mean values ranging nearly fivefold (1.9–7.4 Nm, with single tightening maneuvers spanning from 1.8 to 8.9 Nm). Previous biomechanical investigations have clearly demonstrated that the immediate mechanical stability and fixation integrity of spinal instrumentation critically depend on secure locking screw fixation [16,17].

It is important to emphasize that recommended final fastening torques are strictly implant-specific, governed by proprietary thread pitch, saddle geometry, and surface coatings. In standard commercial thoracolumbar pedicle screw systems, manufacturer-recommended final torques typically range between 8.0 and 12.0 Nm to ensure robust rod purchase and fatigue resistance [18,19]. Although our custom-modified high-strength screw construct was developed specifically to permit repeated non-destructive bench measurements and cannot be equated 1:1 to a specific commercial set-screw interface, the 8.0–12.0 Nm literature range provides a relevant biomechanical benchmark.

In this context, the mean manual torque generated by surgeons (4.52 Nm, with individual averages as low as 1.9 Nm) highlights a substantial discrepancy between subjective tactile force perception and established mechanical tightening thresholds. Such wide inter-individual variability underscores that relying purely on manual tactile feedback introduces unpredictable mechanical variation into spinal construct assembly [16,17].

The significant differences associated with grip technique and surgeon positioning highlight the influence of ergonomic factors on applied torque. Two-handed tightening produced significantly higher torque, demonstrating that bimanual force application markedly increases the mechanical load delivered to the construct, which warrants caution when mechanical limiters are absent. The observation that contralateral screws are tightened more forcefully suggests that awkward positioning may compromise tactile feedback, prompting surgeons to apply additional force.

Interestingly, institutional use of torque-measuring instruments did not correlate with torque magnitude. This may reflect inconsistent instrument use, inadequate calibration, or surgeons overriding torque limits based on tactile sensation. It is also possible that surgeons familiar with torque instruments develop better awareness of force application, paradoxically leading to more variable torque values when these instruments are unavailable.

The clinical implications of our findings are significant. Optimal screw tightening torque is critical for construct stability, as inadequate tightening may lead to implant loosening and failure, while excessive torque may risk screw stripping or bone damage [20,21]. The wide variability observed in this study demonstrates that purely manual tightening without mechanical feedback introduces substantial mechanical heterogeneity across surgeons and individual screw positions.

4.1. Limitations

Several limitations should be acknowledged. First, although the synthetic composite spine model provided a highly reproducible platform across all 220 measurements, its mechanical properties differ from living human bone. Native vertebrae exhibit pronounced heterogeneity, with cancellous bone possessing a significantly lower elastic modulus ($E \approx 0.1$ – 0.5 GPa) compared to cortical bone ($E \approx 12$ – 18 GPa), which undergoes

viscoelastic deformation, micromotion at the screw-bone interface, and micro-fracturing during high-torque insertion. These dynamic *in vivo* phenomena, along with the absence of soft-tissue envelope resistance and intraoperative bio-lubrication, modify tactile feedback. Consequently, while our bench model accurately captures surgeon-dependent motor variability under standardized conditions, absolute torque values cannot be directly extrapolated to live clinical settings. Future translational studies utilizing human cadaveric specimens with intact ligamentous structures will be valuable to quantify the modulating effect of real bone compliance on tactile torque control. Furthermore, tightening torque was estimated from loosening torque using calibration curves rather than measured directly during screw tightening. This indirect measurement strategy was deliberately adopted to preserve clinical authenticity: it allowed participating surgeons to use a standard, unmodified surgical screwdriver identical in handle geometry, grip surface, and weight to instruments used in operating theaters, thereby avoiding any artificial alteration of natural hand ergonomics or tactile force feedback that bulky sensorized handles or specialized torque wrenches would introduce. Consequently, while the reported torque values represent estimated rather than directly recorded figures, the calibration analyses demonstrated strong linear relationships between loosening and reference tightening torque across all screw positions ($R^2 = 0.866\text{--}0.977$), negligible overall systematic bias, and relatively low variability of the mean calibration ratios across screw positions ($CV = 5.03\%$). The Bland–Altman limits of agreement nevertheless indicate measurement variability at the individual measurement level, which should be considered when interpreting the absolute estimated torque values. Future studies using direct real-time measurement of tightening torque may provide further validation of these findings. Second, the study was limited to a single screwdriver geometry; results might differ with other instrument designs. Third, the relatively small sample size and single-country setting may limit generalizability. Finally, while surgeon demographic and clinical experience factors were controlled for in our regression models, we did not assess intraoperative physical fatigue or long-term clinical outcomes in patients.

4.2. Recommendations

Based on our findings, we recommend that implant manufacturers provide:

1. Clear specifications for optimal tightening torque for their systems.
2. Calibrated torque-limiting screwdrivers with each implant set.
3. Surgeon education on the importance of standardized torque application.

Surgical training programs should emphasize awareness of ergonomic influences—such as grip technique and patient-relative orientation—on manual force application.

5. Conclusions

Significant variability exists in the torque applied by spine surgeons during screw fastening, influenced by grip technique, surgeon positioning, and individual practice patterns. These findings support the use of torque-limiting instruments in spinal instrumentation to ensure consistent torque delivery and minimize surgeon-dependent mechanical variability during construct assembly. Future research should investigate how this manual variability behaves in cadaveric models under realistic tissue constraints. Future research should investigate the relationship between applied torque and long-term clinical results, as well as develop simplified torque-limiting devices suitable for routine surgical use.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from all participating spine surgeons to publish this paper.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

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