TechMecha RoboSphere | 2026, Vol. 1, No.1, 15 – 21 | ISSN Online: 3155-6019
DOI: https://doi.org/10.62718/vmca.tech-robo.1.1.SC-0126-004

OPEN ACCESS

Error Analysis on Ball Screw and Lead Screw for Proto-Typed CNC-Based Milling

Article History:
Initial submission: 31 March 2026
First decision: 08 April 2025
Revision received: 22 May 2026
Accepted for publication: 18 June 2026
Online release: 01 July 2026

Engr. Danfort Raven E. Inocencio[1]
Wilfredo D. Timajo[2], PhD
Jayros V. Amar[1]

[1]Instructor II, College of Engineering, Rizal Technological University, 704 Boni Avenue, Mandaluyong City, Philippines
[2]Associate Professor V, Rizal Technological University, 704 Boni Avenue, Mandaluyong City, Philippines

Abstract

CNC machines are vital in modern manufacturing, as even minor errors from friction, loading, or vibration impact precision. These errors can be generated from motors, nut and screw friction, loadings, wear and tear, and machine vibrations. This study experimentally evaluates the linear end-travel errors of ball screw and trapezoidal lead screw actuators in a classroom-scale CNC milling platform under low-load conditions (0–4000 g) and three motion profiles (default, accelerated, and decelerated). Each condition was tested through 20 bidirectional cycles, repeated five times, in both individual and simultaneous operating modes. Testing involved 20 cycles per condition repeated 5 times for individual and simultaneous operations. While average errors between both mechanisms showed no significant difference, lead screws exhibited higher errors above 2800g. Errors increased proportionally with load, primarily due to backlash and vibration. Ball screws demonstrated better consistency, especially under heavier loads, owing to reduced friction. The motion controller software used has axes settings that can be configured. Error can be reduced by encoding the error compensation values based on the data from this study, in the "backlash" tab on the axes setting of the controller software.

Keywords: Computer Numerically Controlled (CNC) milling, ball screw, lead screw, error analysis, backlash and vibration, load-dependent accuracy

INTRODUCTION

Accuracy and precision are related but distinct: accuracy denotes closeness to a true value, whereas precision reflects repeatability; consequently, high precision does not necessarily imply high accuracy. As a "Computer Numerically Controlled" (CNC) machine ages, wear in its actuators and drive elements accumulates, progressively diminishing accuracy. Without on-the-fly adjustment, this drift can yield unacceptable positional errors during operation (Wolny, 2018).

In CNC systems, positioning errors arise from both static geometric factors and service-dependent mechanical effects. While geometric misalignment or structural deformation can be corrected during calibration, backlash develops progressively during operation and requires continuous monitoring. Backlash originates from mechanical clearance, friction, and compliance within drive components and becomes more pronounced under repeated bidirectional motion. Its magnitude is influenced by actuator type, loading conditions, acceleration and deceleration profiles, and rotational speed (Grioli et al., 2015).

Backlash represents a dynamic error source because it evolves with usage rather than a one-time calibration issue. Therefore, understanding how operational conditions affect backlash behavior is essential for maintaining long-term positioning performance.

CNC machines often use uniform actuator types across all axes. When a drive mechanism fails, replacement with an identical actuator is preferred. Availability and cost constraints particularly in educational settings, may necessitate substituting one actuator type for another or operating mixed configurations (e.g., one axis with a ball screw and another with a lead screw). Despite the practical relevance of this scenario, limited experimental data exist comparing the error performance of ball screws and lead screws under low-load, classroom-scale conditions, especially when axes operate simultaneously. This constraint raises an important but underexplored question: Can ball screw and lead screw actuators operate together in a mixed configuration without introducing unacceptable positioning discrepancies?

Existing literature provides theoretical and simulation-based comparisons of screw mechanisms but offers limited experimental data. This gap is especially relevant in educational and prototyping environments, where actuator substitution decisions are often driven by practical constraints and not just optimal design selection. This study therefore investigates the linear end-travel errors of ball screw and lead screw actuators under controlled low-load conditions (0–4000 g) and three motion profiles (default, accelerated, and decelerated). Tests are conducted in both individual and simultaneous operating modes to simulate realistic CNC axis coordination. By statistically comparing positioning errors across load ranges and dynamic profiles, this work aims to (1) determine the operating conditions under which the two actuator types differ significantly and (2) provide practical guidance for actuator substitution and controller-level backlash compensation in low-load CNC systems.

The scope of this study is limited to classroom-scale CNC-based milling platforms operating within low-load conditions. The conclusions of this study are based and limited to the following conditions: Low-load conditions (0–4000 g); Classroom-scale CNC platforms; Short-term cyclic testing (20-cycle runs); and Closed-loop stepper motor systems. Conclusions should therefore be interpreted within this context and not directly generalized to heavy-duty industrial CNC machines.

LITERATURE REVIEW

Ball screws and trapezoidal lead screws are the most widely used linear actuators in CNC motion systems. Their mechanical differences significantly influence error characteristics. Ball screws use rolling contact through recirculating ball bearings between the nut and screw shaft. This configuration reduces friction, improves mechanical efficiency, and enhances repeatability underload. As a result, ball screws are commonly used in higher-precision and higher-load applications. Lead screws, in contrast, operate through sliding contact between the nut and screw threads. Although more economical and simpler in construction, sliding interaction increases friction and vibration, which can contribute to greater backlash and positioning deviation (Tsai et al., 2016). Due to their lower cost, lead screws are frequently used in classroom-scale and hobby-type CNC systems. Comparative reviews have generally concluded that ball screws exhibit superior accuracy and reduced wear compared to lead screws (Dhaware et al., 2019). Many of these analyses emphasize general performance characteristics rather than experimentally controlled evaluations under low-load and educational-scale CNC conditions.

Beyond mechanical construction, actuator performance is strongly influenced by applied load and motion dynamics. Du et al. (2016) demonstrated that deformation in ball screw systems increases nonlinearly with applied force. Although their investigation focused on simulation and higher load ranges, the study confirmed that load disturbances directly affect positioning stability.

Wang et al. (2024) demonstrated that deformation under complex loading is directly related to feed-shaft position error and can be modeled for compensation. Motion dynamics are similarly important. Tsai et al. (2016) showed that vibration suppression must be considered in servo-feed drive motion planning, which supports the inclusion of different motion profiles when evaluating end-travel accuracy.

From a control perspective, Gan et al. (2023) treated backlash as a practical CNC accuracy problem and showed that it can be detected and compensated in real time when the error source is sufficiently characterized.

Most published studies emphasize industrial feed drives, analytical modeling, or compensation strategies for ball-screw systems. Comparatively little experimental work has examined the relative end-travel performance of ball screws and trapezoidal lead screws under low-load, classroom-scale CNC conditions, especially when mixed actuator configurations may be used and axes may operate individually or simultaneously. Different actuator types may need to operate together because of maintenance, cost, or availability constraints. The present study addresses this gap by experimentally comparing linear end-travel error across actuator type, load level, motion profile, and operating mode in a classroom-scale CNC milling platform.

METHODS

The experimental dataset for this study is comprised of end-travel positioning cycles of classroom-scale CNC linear stages operated under low-load conditions (0 to 4000 g), three motion profiles (default, accelerated, decelerated), two actuator types (trapezoidal lead screw and ball screw), and two operating modes (individual and simultaneous). The design was selected because variations in load category and motion profile can influence backlash-related positioning error, and these effects can be observed during repeated bidirectional reversals under controlled speed conditions. The tested sample consisted of two structurally identical stages, one equipped with a lead screw and the other with a ball screw. Each actuator was evaluated at eleven load levels (0 to 4000 g at 400 g intervals). For each actuator, profile, load, mode condition, five (5) runs were conducted, with each run comprising 20 cycles and the end-travel error recorded after the 20th cycle. This procedure yielded 660 error observations in total (2 actuators, 3 profiles, 11 loads, 2 modes, 5 runs). The replication structure was designed to support comparisons of actuator performance across representative loading and motion conditions.

Two structurally identical platforms were fabricated using aluminum frames, with the only difference being the actuator mechanism. One setup was equipped with a ball screw drive, while the other utilized a trapezoidal lead screw. Both configurations included ball-type linear guide rails mounted parallel to the actuator to ensure precise linear motion and reduce mechanical deflection during testing. Each actuator was driven by a JSS57P2N closed-loop stepper motor, directly coupled to the screw shaft and supported on the opposite end by pillow bearings. The motors incorporated rotary encoders to allow real-time position feedback and enhance motion control accuracy.

Motor commands were managed through a CNC USB MACH3 controller board, which supports four-axis motion control via a USB-C interface. The system was programmed using standard G-codes, allowing for precise and repeatable motion sequences. The control software also offered a backlash compensation feature, accessible via the "Backlash" tab under axes settings, enabling integration of experimentally derived error correction values.

To capture linear displacement errors, precision dial gauges were mounted opposite each actuator mechanism. The gauges were calibrated to zero before each test sequence. After 20 complete motion cycles per trial, the deviation from the zero position on the dial indicator represented the accumulated linear error for that condition.

The actuators were subjected to eleven different loading conditions, ranging from 0 to 4000 grams in 400-gram intervals. Motion was performed under three speed profiles:

- Default speed: 6985 mm/minute (275 inches/minute)
- Accelerated speed: 10160 mm/minute (400 inches/minute)

- Decelerated speed: 3810 mm/minute (150 inches/minute)

Each loading condition underwent 20 motion cycles, and this procedure was repeated five times per configuration to ensure statistical reliability. Tests were conducted in both individual and simultaneous actuator modes to simulate real-world scenarios of axis coordination.

RESULTS

This section presents the comparative end-travel error behavior of ball screw and trapezoidal lead screw mechanisms across varying load conditions, motion profiles, and operating modes. Error differences in millimeters (lead screw minus ball screw) are summarized in Tables 1 and 2 and illustrated in Figures 1 and 2.

Positioning error generally increased with load for both actuator types across all test conditions. As shown in Table 1 (Individual Mode), error differences between the lead screw and ball screw remained negligible at lower loads (0–2400 g) across all motion profiles. The default profile exhibited near-zero deviation within this range, while the accelerated and decelerated profiles showed only minor fluctuations.

Beginning at approximately 2800 g, divergence between actuator types became more noticeable in Individual Mode. This trend is most pronounced under the accelerated profile, where error difference increases steadily beyond mid-range loads and reaches higher values at 2000 g and above. Under default speed, error remains minimal overall but shows slight variability at higher loads, including a small negative deviation at 3200 g. This indicates that under isolated conditions, the ball screw may temporarily exhibit slightly greater error than the lead screw; however, this behavior is not sustained across subsequent load levels.
Table 2 (Simultaneous Mode) demonstrates that error differences remain relatively small and stable across the entire load range. Although minor fluctuations are observed under accelerated and decelerated profiles, no consistent load-dependent amplification occurs. The default profile remains near zero for most conditions. These results indicate that simultaneous axis operation does not significantly magnify positioning discrepancies between actuator types within the tested load range.

Table 1
Error Difference of Lead Screw and Ball Screw in millimeters per loading condition for Individual Mode.

Load (grams)	Default speed	Accelerated	Decelerated
0	0	0	0
400	0	0	0
800	0	0.004	0
1200	0	0.002	0
1600	0	0.004	0
2000	0	0.01	0
2400	0	0.008	0
2800	0.002	0.008	0
3200	-0.002	0.008	0.008
3600	0.006	0.01	0.008
4000	0.002	0.008	0.006

Table 2
Error Difference of Lead Screw and Ball Screw in millimeters per loading condition for Simultaneous Mode.

Load (grams)	Default speed	Accelerated	Decelerated
0	0	0.004	0.002
400	0	0.008	0.008
800	0	0.004	0.018
1200	0	0.002	0.006
1600	0	0.004	0.01
2000	0	0.004	0.002
2400	0	0.008	0.012
2800	0	0.004	-0.002
3200	0.006	0	0.004
3600	0	0.004	0.008
4000	0	0.004	0.008

Tables 1 and 2 present the numerical error differences between the lead screw and ball screw mechanisms across load conditions and motion profiles, while Figures 1 and 2 provide a graphical representation of the same data to highlight overall trends.

In Table 1 (Individual Mode), error differences remain near zero for loads up to 2400 g across all motion profiles. This behavior is clearly visualized in Figure 1, where the curves remain close to the horizontal axis within the lower load range. Beginning at approximately 2800 g, the accelerated and decelerated profiles exhibit increased deviation, which appears in the graph as a noticeable upward trend beyond mid-range loads. The slight negative deviation at 3200 g under default speed in Table 1 is also reflected in Figure 1 as a small dip below the zero line.

Table 2 (Simultaneous Mode) shows generally small and fluctuating error differences across the entire load range. In Figure 2, this pattern appears as relatively stable curves with minor variations and no sustained upward trend. The absence of pronounced load-dependent divergence in the graphical representation supports the numerical observation that simultaneous operation does not significantly amplify error differences.

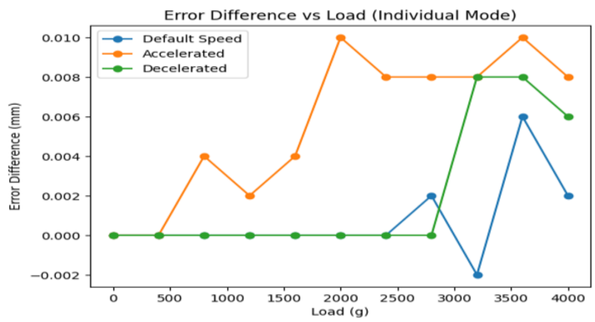

Figure 1
Error Difference vs. Load in three different speeds for Individual Mode

Figure 2
Error Difference vs. Load in three different speeds for Simultaneous Mode

The graphical figures serve as an overall visual confirmation of the tabulated results, illustrating the load-dependent divergence observed in Individual Mode and the comparatively stable behavior under Simultaneous Mode.

Motion profile influences the magnitude of error difference more noticeably at higher loads. Accelerated and decelerated conditions tend to produce larger deviations compared to default speed, particularly in Individual Mode. This supports the hypothesis that dynamic effects such as vibration and inertial interaction that has become more significant as load increases. Statistical analysis also indicates that these differences remain insignificant for most test conditions, except under specific high-load deceleration scenarios.

Independent-samples t-tests were conducted at 0.05 significance level (two-tailed, df = 8; critical value = 2.306) to evaluate differences between actuator types across load conditions and motion profiles.

For loads up to 2800 g, no statistically significant differences were observed between the ball screw and lead screw mechanisms under either Individual Mode or Simultaneous Mode across all motion profiles ($|t| < 2.306$). This indicates comparable positioning performance within the low-load range.

At higher loads ($\geq$ 3200 g), statistically significant differences were detected only under the decelerated profile in Individual Mode. In this condition, the computed t-value exceeded the critical value ($t = 2.45 > 2.306$), indicating divergence between actuator types. No other high-load conditions exhibited statistically significant differences.

Under Simultaneous Mode, no statistically significant differences were observed across any load range or motion profile.

The overall statistical analysis confirms that lead screw and ball screw mechanisms perform comparably under most low-load classroom-scale CNC operating conditions, with divergence occurring only under specific high-load deceleration scenarios.

DISCUSSION

Findings indicate that load magnitude is the primary factor influencing positioning error divergence between ball screw and lead screw mechanisms. While statistical analysis revealed no significant difference across most test conditions, graphical trends demonstrate that error differences begin to increase beyond approximately 2800 g.

This load-dependent behavior aligns with the findings of Du et al. (2016), who demonstrated that deformation increases nonlinearly with applied force in screw-driven systems. Their study emphasized higher load magnitudes and the nonlinear relationship between load and deformation supports the observed increase in positioning error at heavier loads in the present experiment. As load increases, mechanical compliance and deformation within the screw–nut interface contributes to cumulative end-travel deviation during cyclic motion.

Both actuator types exhibited similar performance below 2800 g, suggesting that within low-load classroom-scale CNC applications, mechanical differences between rolling-contact (ball screw) and sliding-contact (lead screw) systems do not significantly influence positioning accuracy.

Dynamic motion conditions further influence error magnitude, particularly under acceleration and deceleration phases. The results show that divergence between actuator types becomes more pronounced during decelerated motion at higher loads.

This behavior may be attributed to vibration and inertial interactions. High acceleration and deceleration rates introduce dynamic forces that amplify mechanical compliance and backlash effects. Tsai et al. (2016) noted that vibration induced by rapid motion profiles can degrade positioning quality, particularly in systems with greater frictional interaction. Because lead screws rely on sliding contact, friction-generated vibration may contribute to slightly higher error at heavier loads.

The accelerated profile under Simultaneous Mode demonstrated higher error at lower loads in some cases. This may be explained by reduced damping at lighter masses. With lower inertia, actuator vibration may resonate more strongly, whereas heavier loads provide passive damping, reducing oscillatory displacement. This observation highlights the interaction between load inertia and dynamic response in screw-driven systems.

Consistent trends, although statistical differences were limited, indicate that lead screws tend to generate slightly larger errors at heavier loads ($\geq$ 3200 g), especially during deceleration. For applications requiring higher precision under moderate-to-heavy loads, ball screws may therefore provide more consistent performance. For classroom-scale CNC systems operating within low-load ranges ($\leq$ 2800 g), the two mechanisms demonstrate comparable positioning behavior.

One practical concern addressed in this study was whether mixed-actuator configurations (ball screw and lead screw operating concurrently) would introduce additional positioning discrepancies. The results indicate that simultaneous operation did not produce statistically significant differences across any load range. Error trends remained stable and comparable to individual-axis operation. This suggests that, within the tested load and speed conditions, actuator interaction does not amplify positioning error. For educational and prototyping environments, this finding is particularly relevant. It implies that actuator substitution due to availability constraints may not necessarily compromise system performance under low-load conditions.

In such cases, software-level backlash compensation may effectively mitigate residual differences without requiring mechanical replacement. Future research may explore long-term wear effects, thermal influences, and higher dynamic loading conditions to further characterize actuator performance.

Author contributions. Danfort Raven E. Inocencio: Writing-original draft, Resources, Methodology, Project administration, Writing-review & editing | Wilfredo dL. Timajo: Conceptualization, Supervision, Validation | Jayros V Amar: Software, Data curation, Formal analysis, Writing-original draft,

Conflict of interest. The authors declare that the research was conducted without commercial or financial relationships that could be construed as a potential conflict of interest.

Funding source. This research received no external funding.

Artificial intelligence use. AI-assisted language editing was performed using ChatGPT, Quilbot; authors reviewed and approved all contents.

Ethics approval statement. This research involved only experimental testing of mechanical components (CNC-based systems) and did not include human participants, human data, or animal subjects. Consequently, ethical approval from an institutional review board or ethics committee was not required.

Data availability statement. All data supporting the findings of this study are included within the manuscript and its supplementary materials.

Acknowledgement. (Not available)

REFERENCES

Dhaware, Y., Palkuntwar, P., Narkhede, H., Meher, R., Chavan, P., & Gandevia, B. (2019). Review on comparative analysis of ball screw & lead screw. *International Research Journal of Engineering and Technology (IRJET), 6*(6).

Du, Z., Zhang, X., & Tao, T. (2016). Study of the dynamic characteristics of ball screw with a load disturbance. *Mathematical Problems in Engineering, 2016*, Article 8208241.

Gan, L., Wang, L., & Huang, F. (2023). Adaptive backlash compensation for CNC machining applications. *Machines, 11*(2), 193. https://doi.org/10.3390/machines11020193

Grioli, G., Wolf, S., Garabini, M., Catalano, M., Burdet, E., Caldwell, D., Carloni, R., Friedl, W., Grebenstein, M., Laffranchi, M., Lefeber, D., Stramigioli, S., Tsagarakis, N., Damme, M., Vanderborght, B., & Albu Schaeffer, A. (2015). Variable stiffness actuators: The user's point of view. *The International Journal of Robotics Research, 34*(6), 727–743. https://doi.org/10.1177/0278364914566515

Tsai, M., Huang, H., Yang, S., & Chou, C. (2016). Integrating input shaping technique with interpolator for vibration suppression. In *2016 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)* (pp. 12–15). IEEE.

Wang, T., Chen, G., Sun, J., Huang, Y., & Zhang, S. (2024). Prediction and compensation of position error based on deformation analysis of ball screw under complex loads. *The International Journal of Advanced Manufacturing Technology, 134*, 1729–1750. https://doi.org/10.1007/s00170-024-14239-7

Wolny, R. (2018). Analysis of accuracy of 5-axis CNC milling machine through standard and modified circular test. *Mechanik, 91*(10)