Predictive Modeling of Laser-Cut Hypotubes

A Computational Framework for Catheter Design

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Abstract

Minimally invasive medical procedures increasingly rely on catheter-based interventions, where thin, flexible tubes are navigated through the vascular system to reach treatment sites without large incisions [4]. To function effectively, catheters must balance flexibility, strength, and operator control. Traditional catheter reinforcement methods such as braid or coil often fail to deliver the optimal combination of these properties for modern procedures [2].

Hypotubes are thin-walled metal tubes used in medical devices and offer a customizable alternative when precision laser cutting is applied to create geometric patterns. Unlike conventional catheter reinforcement, laser-cut hypotube enables fine-tuning of bending, stretching, and torsional behavior [7], allowing catheters to access anatomical regions previously considered inaccessible.

However, predicting the mechanical performance of these complex geometries is challenging. Engineers must evaluate longitudinal rigidity (resistance to stretching), flexural rigidity (resistance to bending), and torsional rigidity (resistance to twisting) [3]. These parameters determine whether a catheter can navigate vessels, maintain positioning, and transmit forces effectively from operator to treatment site.

Existing tools such as CathCAD® were designed for conventional reinforcement and cannot accommodate the variability of laser-cut designs [1]. As a result, engineers often rely on costly, time-intensive prototyping to assess how laser-cut hypotube design parameters influence device performance.

This research introduces a computational modeling solution developed by a University of Colorado Boulder student team in collaboration with Meddux. Building on spring-constant theory and volumetric approximation methods, the team created a Python® program with a graphical user interface (GUI) and console-based calculator for real-time parameter assessment in both metric and imperial units. The preliminary model focuses on the Interrupted Spiral cutting pattern, incorporating eight critical design inputs, including kerf width, cut angle, pitch variation, and cuts per revolution. Tensile and three-point bend testing demonstrated ±20% model accuracy, while statistical analysis confirmed high model reliability across the tested parameter space.

This predictive capability has the potential to lessen reliance on iterative prototyping, offering a pathway to shorten development timelines from months to weeks. The model also provides a scalable foundation for predicting performance other laser-cut hypotube patterns, bridging traditional engineering analysis with the demands of precision manufacturing.

Introduction

The rapid advancement of minimally invasive procedures has created demand for highly specialized catheter systems capable of navigating complex anatomical pathways. Laser-cut hypotubes provide enhanced flexibility and strength through precise geometric patterning but require a distinct modeling approach due to its highly variable geometry.

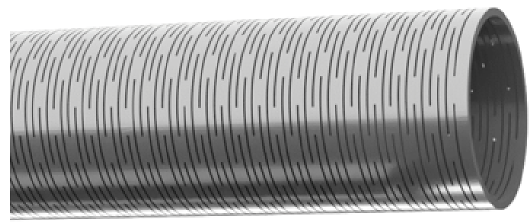
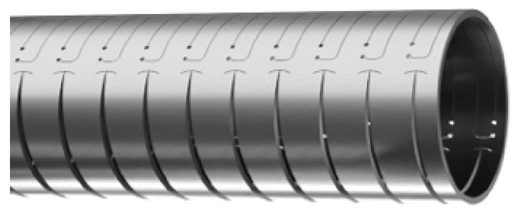
Interrupted Spiral Pattern	
"Dog Bone" Pattern	
"Segmented" Pattern	

Figure 1. *Common laser-cut hypotube patterns*

Image Credit: Symmetry Laser

This work addresses the gap in available tools by developing a predictive model for laser-cut hypotube mechanical performance, starting with the Interrupted Spiral pattern. The model predicts key mechanical properties, including longitudinal and flexural rigidity, based on defined geometric and material parameters. Inputs include material type (Stainless Steel 304 or 316), kerf width, cut angle, uncut length, inner and outer diameters, cuts per revolution (3.0–4.5), tube length, and pitch. A prediction accuracy within ±20% of empirical test results was established as the benchmark for success.

Software Architecture and System Design

A team from the University of Colorado Boulder, in collaboration with Meddux, developed a custom software platform in Python® with GUI and a console-based calculator for validation and testing.

The GUI comprises two tabs for imperial and metric units and one for metric, which are linked to a unified computational engine that operates in SI units. Each interface includes:

- A material selection module supporting Stainless Steel 304 and 316
- Entry fields for tensile and flexural modulus
- Input grids for the eight critical geometric parameters of the laser-cut hypotube
- Radio buttons for selecting cuts per revolution (3.0–4.5)
- Real-time output fields for longitudinal and flexural rigidities

A single “Compute” action initiates the full processing pipeline: input validation, unit normalization, geometric parsing, stiffness computation, and post-processing output, including automatic reconversion for imperial results. Additional features—such as mirrored angle input, bidirectional unit converters, and pre-loaded dropdown menus—enhance usability and reduce the risk of input errors.

A standalone Python® script mirrors the computation engine, supporting algorithm validation and automated unit testing. Operations include dimensional conversions, theta-angle calculation, kerf-width integration, segment-length parsing, cross-sectional area weighting, and stiffness computation using material modulus inputs. All computed values are structured into an exportable dictionary and displayed in a clear hierarchical format for traceability.

Predictive Model Design

The modeling approach began with standard spring-constant equations for hollow tubes, which provide a baseline for unmodified structures. These equations were modified to account for the structural changes introduced by laser cutting. A key innovation was the use of volumetric and cross-sectional analysis to quantify material removed during cutting, with proportional adjustments applied to spring constants to improve the accuracy of the predictive model. To ensure the model reflects actual material behavior, Young’s moduli derived from tensile and flexural stress-strain tests were incorporated.

Experimental Methods and Validation

Validation of the predictive model required comprehensive mechanical testing to establish baseline properties and verify computational accuracy. Two protocols were employed: tensile testing for longitudinal rigidity and three-point bend testing for flexural rigidity.

The experimental framework was structured in two phases:

- **Preliminary testing** for model calibration and refinement of predictive equations.
- **Validation testing** to verify performance against accuracy thresholds.

This phased approach was necessary given the limited availability of published data for laser-cut hypotubes. Testing protocols adhered to industry standards and were conducted using a universal testing machine.

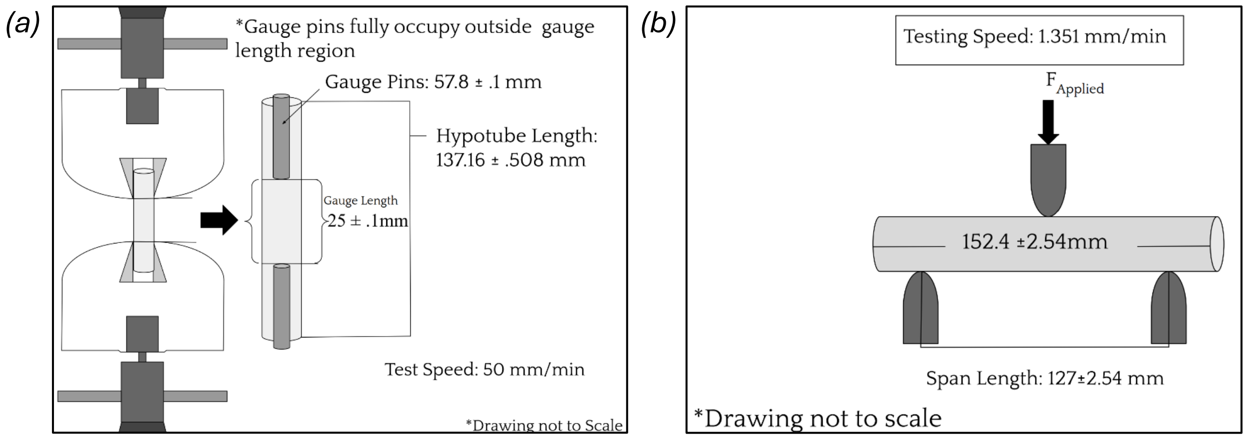


Figure 2. *Mechanical testing setups: (a) Tensile; (b) Three-point bend.*

A critical component of model validation was determining Young's modulus for laser-cut hypotubes with varying degrees of material removal. Three variants with distinct cut patterns and volumetric loss percentages were tested to establish relationships between design parameters and mechanical performance.

Spring constants were extracted by analyzing the linear elastic deformation region of the stress-strain curves. Consistent sample preparation minimized variability and ensured reliable results.

Statistical analysis confirmed reliability of the data. The coefficient of variation for flexural testing was 6%, well within the acceptable range for most engineering applications. Normal probability analysis indicated all data points fell within expected confidence bounds, with minimal deviation from theoretical distributions.

Results and Analysis

The validation phase focused on evaluating the predictive accuracy of the model through direct comparison with experimental results. Spring constants extracted from tensile and flexural testing were compared to model predictions.

- **Longitudinal stiffness**: Predictive values deviated 0.9–12.1% from experimental measurements, with most trials under 6%. Predicted trends consistently matched experimental results, confirming appropriate correlation between design parameters and mechanical performance.

- **Flexural properties**: Predicted values deviated 2.9–14.4% from experimental measurements, with many predictions under 10%. This agreement indicates that the model's geometric and volumetric analysis effectively captured the parameters governing flexural response.

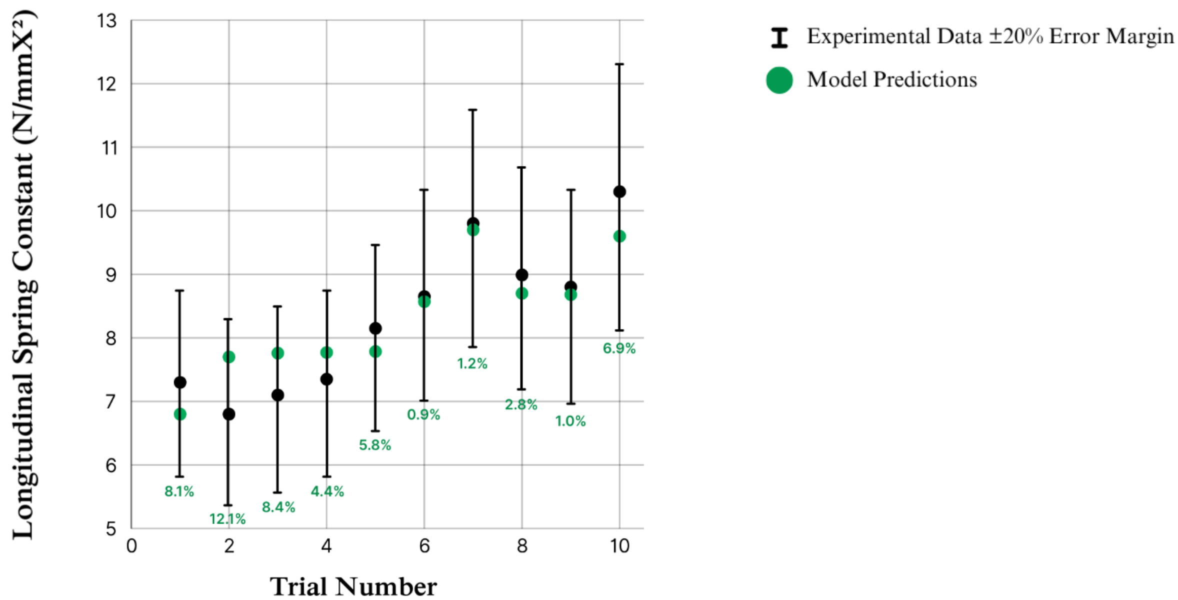


Figure 3. *Longitudinal Rigidity Testing Results*

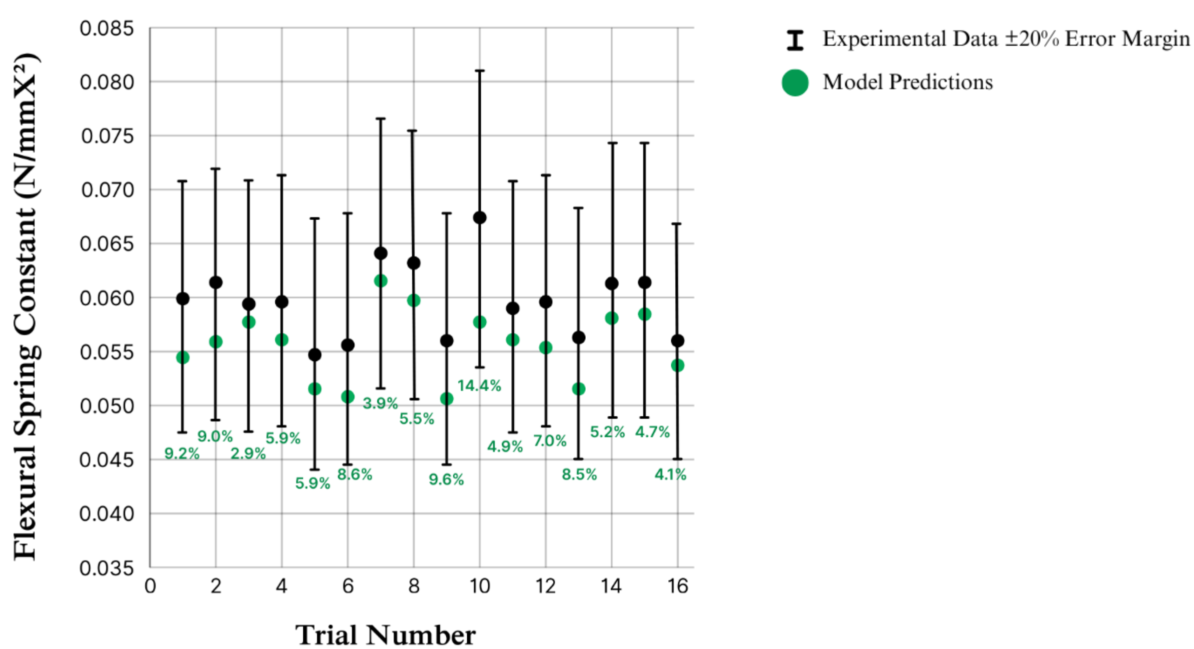


Figure 4. *Flexural Rigidity Testing Results*

Statistical Analysis

A one-sample t-test conducted across all trials yielded a t-statistic of –23.26 with a p-value of 9.22×10^{-23}, providing strong statistical evidence that the model's average predictive error was significantly below the 20% tolerance threshold. This result confirmed that the modeling approach met design accuracy requirements and demonstrated reliability across tested configurations.

Extended Validation Testing

Further testing on hypotubes with varying geometric parameters showed that, when accurate empirically derived material properties were used as inputs, the model achieved exceptional precision. Percentage errors between predicted and measured spring constants ranged from 0.08% to 0.16%. These results confirmed that the model's effectiveness when interpolating between previously tested designs.

Model Limitations and Scope Definition

While the model significantly reduces the need for physical prototypes by reliably estimating spring constants when effective material properties are known, it cannot fully replace physical testing for novel hypotube configurations that deviate substantially from the original dataset. Establishing a direct, generalizable relationship between volumetric loss and effective material properties remains challenging with the current data, limiting the model's ability to extrapolate to untested geometries or material distributions.

Despite these constraints, validation demonstrated that the predictive model meets engineering accuracy requirements within its intended scope. The strong agreement between modeled and measured spring constants across both flexural and axial loading modes indicates that the model can be confidently applied to design iterations within the validated parameter range.

Discussion and Future Scope

The current modeling approach demonstrates strong performance for longitudinal rigidity predictions, with validation results confirming reliable accuracy within engineering tolerances. However, flexural rigidity calculations present opportunities for improvement. Initial implementations using volumetric and geometric approximations revealed discrepancies between predicted and measured values.

A key factor contributing to these variations was the theoretical treatment of moment of inertia calculations. The current approach assumes idealized cross-sections that may not fully capture the geometric variability introduced by laser-cut patterns along the hypotube length. Future development should prioritize the derivation of more sophisticated moment of inertia models that accurately reflect the true geometric complexity of these structures.

Conclusion

The University of Colorado Boulder student research successfully developed a foundational modeling framework specifically designed for laser-cut hypotube catheters, addressing a critical gap in existing design tools. The Python®-based implementation provides Meddux engineers with validated capabilities for evaluating longitudinal and flexural rigidity, properties essential for catheter performance in complex anatomical environments.

The modeling approach demonstrates strong predictive accuracy within established engineering tolerances, particularly for longitudinal rigidity. The research established a comprehensive methodology for integrating empirical testing with computational modeling, creating a robust framework for continued refinement and providing a solid foundation for practical design applications.

By delivering reliable predictive capabilities for laser-cut hypotube performance, this work supports the advancement of next-generation catheter systems capable of navigating increasingly complex anatomical pathways with improved precision and reliability. Future development should focus on expanding the validated parameter space and incorporating additional mechanical properties. This research represents an important step toward more sophisticated and reliable tools for medical device engineering, ultimately contributing to improved patient outcomes by enabling more precise and dependable device navigation during minimally invasive procedures.

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