Modelling and Finite Element Analysis of a Tendon-Driven Continuum Robotic Spine for Quadruped Applications

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Abstract

This ongoing study investigates the modelling and finite element analysis (FEA) of a tendon-driven continuum robotic spine intended for quadruped robots. Existing rigid torsos limit terrain adaptability, while soft or continuum spines are compliant but often suffer from low load-bearing capacity and from models, such as constant curvature, that cannot capture non-uniform deformation under load. This work combines a kinematic description of a three-tendon, disk-segmented spine with a static force-and-moment equilibrium model that includes Coulomb tendon-guide friction, and a nonlinear FEA study of deformation, stress distribution and stiffness under realistic loads. The first stage reproduces a published reference configuration to benchmark the FEA workflow; later stages evaluate candidate materials and design parameters. This version presents the motivation, literature review, mathematical model, FEA methodology and study plan. Results and validation will be added in subsequent versions.

Keywords: continuum robotics, tendon-driven mechanism, robotic spine, finite element analysis, quadruped robots, structural simulation

1. Introduction

1.1 Background

Quadruped robots are valued for mobility in unstructured environments such as disaster response, field inspection and exploration. Many current platforms still use rigid torsos or simple spinal mechanisms, which restricts coordination between the fore and hind limbs and reduces adaptability on uneven terrain. Biological spines, in contrast, combine flexibility, load-bearing capability and energy efficiency. This has motivated robotic spines based on continuum and tendon-driven mechanisms, which provide smooth, continuous bending using proximally located actuators [1], [2].

1.2 Problem statement

Tendon-driven continuum structures are compliant, but their low structural stiffness limits load-bearing capacity and positioning accuracy under external loads. Widely used constant-curvature (CC) and piecewise constant-curvature models assume uniform bending and therefore cannot predict the non-uniform deformation that appears when a spine carries load [2], [3]. Cosserat-rod and finite element

approaches can capture this behaviour, but they are computationally heavier and are not always applied to spine-specific architectures with spacer disks, springs and tendon-guide friction.

1.3 Research gap

The three studies reviewed in Section 2 each address part of the problem: a load-bearing spine prototype with a Newton–Euler static model [3], a 3D finite element model that explains friction and compliant-element effects [4], and a Cosserat model that retains finite rigid disk intervals and disk-level tendon loading [5]. A systematic finite element study of a quadruped-oriented tendon-driven spine that links design parameters (segment stiffness, material, tendon routing and friction) to deformation, stress and load capacity, and that is benchmarked against published data, has not been consolidated in a single workflow. This work aims to contribute to that gap.

1.4 Objectives

1. Build a CAD and FEA model of a three-tendon, multi-disk continuum spine and benchmark it against a published reference configuration.
2. Develop a kinematic and static-equilibrium formulation (including Coulomb friction at tendon guide holes) to relate tendon actuation to spine posture and internal loads.
3. Use nonlinear FEA to quantify deformation, von Mises stress and factor of safety under tendon actuation and external load for candidate materials.
4. Identify design parameters that most strongly affect compliance and load-bearing capability, as guidance for quadruped spine design.

2. Literature Review

Three recent studies form the basis of this work. Their methods, findings and limitations, as reported by the authors, are summarised in Table 1.

Table 1. Comparison of reference studies

Ref.	Method	Key findings (as reported)	Limitations noted
[3] Ke et al., 2026	Newton–Euler static model of a 2-DoF spine with cross-universal joints and distributed compression springs; 230 mm prototype tested up to 7.5 kg	Max positional deviation 10.10 mm (4.40% of length); RMSE below 5.68 mm across trajectories; spring stiffness of 20 N/mm chosen from a 10–40 N/mm study	Quasi-static only; end-load configuration; friction coefficient (0.3) taken from literature, not identified experimentally
[4] Raimondi et al., 2024	Abaqus 3D FE model of a Nitinol twin-pivot, tendon-driven robot with nylon tendons, Yeoh tendon model and tendon–disk friction	Average end-effector error fell from 4.1% (conventional model) to 0.80%, and peak error from 13.86% to 1.30%, with an equivalent friction coefficient of 0.35	Run time about 69 min per simulation; nylon tendons suited to prototypes, not metal-disk robots
[5] Wang and	Piecewise Cosserat rod with	Accurate geometric fitting does not	Simulation only, no

Ref.	Method	Key findings (as reported)	Limitations noted
Zhu, 2026	13 rigid disk segments and 12 flexible spans; disk-level tendon load map	guarantee tendon-static supportability; in a 72-case sweep, 52 cases met the strict geometric criterion but only 22 were strictly supported	experimental validation; frictionless guides, gravity and tendon elasticity omitted in the nominal study

Beyond these, classical work provides the modelling foundations used here: constant-curvature kinematics for continuum robots [6], [7], mechanics models of tendon-driven manipulators [8], statics and dynamics with general tendon routing [9], and benchmarking of how model choice affects predicted TDCR behaviour [10]. Friction-aware static models show that tendon–guide friction changes tension distribution and shape [11].

Gap addressed here: a FEA-centred, parameter-driven study of a tendon-driven spine for quadruped use, benchmarked against published data and focused on deformation, stress and load capacity.

3. System Description and Design

3.1 Overall design concept

The spine is modelled as a series of rigid spacer disks (vertebra segments) connected by compliant elements, with three tendons routed through guide holes in the disks at 120° intervals and anchored at an end plate. Pulling individual tendons produces bending in a chosen direction. Spring or compliant elements between disks provide restoring stiffness and passive compliance, in the spirit of the hybrid rigid–compliant architecture of [3].

3.2 Benchmark configuration (Stage 1)

To validate the FEA workflow before introducing new designs, Stage 1 reproduces the reference configuration reported in [3]:

Table 2. Benchmark parameters taken from [3]

Parameter	Value
Total spine length	230 mm
Number of tendons	3, spaced 120° apart
Tendon routing radius, R_d	65.6 mm
Cross-section support height, L_a	23 mm
Spring stiffness, K_s	20 N/mm (initial length 50 mm)
Friction coefficient (tendon–guide)	0.3
Maximum external end load	7.5 kg

3.3 Candidate design variants (Stage 2)

In Stage 2, own design variants will be defined by varying disk geometry, number of segments, tendon routing radius, stiffness of the compliant elements and material. Final dimensions will be added in a later version once the CAD model is frozen. [Author to complete: final design parameters.]

4. Mathematical Modelling

4.1 Kinematics of a segment

Each segment is described by a bending angle θ_i and a deflection (bending-plane) angle ϕ_i. For tendon j of a segment with routing radius R_d and support height L_a, the projected tendon radius in the bending plane and the corresponding tendon length are given in [3] as:

$$R'_{d,j} = R_d \cdot \cos\left(2(j-1)\pi/3 - \phi_i \right)$$

$$L_{c,j} = 2 \left(L_a \cdot \cos(\theta_i / 2) - R'_{d,j} \cdot \sin(\theta_i / 2) \right)$$

The change in tendon length relative to the straight configuration (initial length $2L_a$) is therefore:

$$\Delta L_{i,j} = 2 L_a \left(\cos(\theta_i / 2) - 1 \right) - 2 R'_{d,j} \sin(\theta_i / 2)$$

The pose of disk $i+1$ relative to disk i is expressed with a homogeneous transformation of the form $T = R_z(\phi)\, T_z(L_a)\, R_y(\theta)\, T_z(L_a)\, R_z(-\phi)$, and the end-disk pose follows from the product of the segment transformations [3].

For comparison, the constant-curvature model treats the whole section as one circular arc with fixed length and variable bending angle and direction [6], [7], which implies identical bending in every segment.

4.2 Static equilibrium with friction

Following [3], each disk is treated as a rigid body in static equilibrium under the following loads: compression-spring force F_s, tendon tension F_c, tendon–guide friction F_f, joint support force F_z, gravity F_g, and the external load F_e. For an interior disk i:

$$\Sigma F = 0 \quad \text{and} \quad \Sigma M = 0$$

The force balance sums the spring, tendon, friction, support and gravity contributions on that disk, and the moment balance uses each tendon's lever arm on the disk. Tendon–guide friction follows a Coulomb law:

$$F_{f,i,j} = \mu_s \cdot \left| F_{c,i,j} + F_{c,i-1,j} \right|$$

Tendon tensions must remain non-negative ($F_c \geq 0$). Because the equilibrium equations are coupled and nonlinear, the tensions and segment angles for a target tip position are found with constrained nonlinear optimisation, minimising the sum of squared tendon tensions subject to the equilibrium equations [3].

4.3 Piecewise Cosserat reference formulation

As a higher-fidelity reference, the spine can be described as a piecewise Cosserat rod in which flexible spans carry active strain coordinates and rigid disk intervals suppress deformation [5]. The segment kinematics are:

$g'(s) = g(s)\,\hat{\xi}(s)$, with $\xi(s) = \xi_o(s) + B(s)\,q$

Tendon forces enter through guide points fixed to rigid disks, mapping the tension vector T to generalised loads:

$Q_{ten}(q, T) = A_{ten}(q) \cdot T$, with equilibrium $R(q, T) = Q_{int}(q) + Q_{ext}(q) + Q_g(q) - Q_{ten}(q, T) = 0$

This formulation will be used to cross-check FEA results qualitatively; it is not re-derived in full here.

5. Finite Element Modelling and Simulation Setup

5.1 CAD model and materials

The spine will be modelled in SolidWorks (or UG NX) and imported into the FEA package (e.g., ANSYS). Nominal material properties for the candidate structural materials are listed in Table 3 and will be replaced by datasheet or tested values before results are reported.

Table 3. Nominal material properties (to be verified against datasheets)

Material	Young's modulus (MPa)	Poisson's ratio	Density (kg/m³)
Nylon (PA)	2000	0.35	1150
TPU	25	0.45	1200
Aluminium	70000	0.33	2700

Compliant elements (springs or flexures) and tendons will be modelled following the approach of [4]: beam or spring elements for tendons, contact with friction between tendons and guide holes, and rigid-body coupling for disks where appropriate.

5.2 Meshing, contacts and boundary conditions

The base disk is fixed. Tendon loads or prescribed tendon displacements actuate the spine, and external end loads (up to the benchmark value) are applied at the distal disk. Tendon–guide contacts use a Coulomb friction coefficient in the range 0.1–0.35 as reported in [3] and [4]. A mesh-convergence study will be run before any result is accepted.

5.3 Simulation procedure

1. Import the CAD model into the FEA software.
2. Assign material properties and element types.
3. Generate the mesh and perform a mesh-convergence check.
4. Define contacts, friction and boundary conditions.
5. Apply tendon actuation and external loads in incremental steps.

6. Solve using nonlinear static analysis (large deflection enabled).
7. Post-process deformation, von Mises stress and reaction forces.
8. Compare with the analytical model (Section 4) and the published benchmark data.

5.4 Planned outputs and metrics

Total and per-segment bending angles; tip position and positional deviation; von Mises stress and factor of safety per material; tendon tension and shortening; and RMSE against the benchmark data of [3].

6. Results and Discussion

Status: pending. No numerical results are claimed in this version. Table 4 lists the planned analyses; results will be added after the simulations are completed and verified.

Table 4. Study plan and status

Stage	Analysis	Status
1	CAD model of benchmark configuration	[Ongoing]
1	FEA of benchmark under tendon actuation, no load	[Ongoing]
1	FEA of benchmark under 7.5 kg end load and comparison with [3]	[Ongoing]
2	Material comparison (nylon, TPU, aluminium): deformation, stress, factor of safety	[Ongoing]
2	Sensitivity to friction coefficient and compliant-element stiffness	[Ongoing]
3	Comparison with analytical (Newton–Euler / constant-curvature) predictions	[Ongoing]

7. Expected Contributions and Limitations

Expected contributions. (i) A benchmarked FEA workflow for tendon-driven continuum spines; (ii) quantified effects of material, stiffness and friction on deformation and stress; (iii) design guidance for quadruped spine modules.

Limitations. The study is simulation-based and quasi-static. Dynamic effects, tendon elasticity and creep, and full-robot locomotion loads are outside the current scope. Without a physical prototype, accuracy claims will be limited to agreement with published experimental data.

8. Conclusion and Future Work

This preprint documents an ongoing study on the modelling and FEA of a tendon-driven continuum robotic spine for quadruped applications. The motivation, literature gap, mathematical model and simulation plan are presented. Future versions will report benchmark validation, material and parameter studies, and design recommendations. Longer-term work includes prototype fabrication, experimental validation and dynamic modelling for locomotion.

Declarations

Author contributions. Eshant Rai: conceptualisation, methodology, simulation, writing.

Competing interests. The author declares no competing interests.

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Data availability. Models and data will be shared in the OSF project once results are finalised.

Use of AI assistance. An AI assistant (Claude, Anthropic) was used to help structure this manuscript from the author's topic, the cited reference papers and a journal template. The author is responsible for the content, and all cited statements should be checked against the original papers.

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