

Structural Optimization of a Tendon-Driven Soft Robotic Eye Joint for the Social Robot HARU

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Abstract—Tendon-driven soft actuators for social robots must balance compliance in the intended degree of freedom (DoF) with sufficient stiffness in unintended DoFs to prevent undesirable deformations. This challenge is particularly relevant for robotic eye joints, where the eye assembly can induce out-of-plane motions that compromise natural gaze behavior. To address this issue, we investigate the structural optimization of a tendon-driven soft eye actuator for HARU, a tabletop social robot for children. Three backbone cross-sectional geometries were analyzed through inertia-based metrics and nonlinear Finite Element Analysis (FEA). Response Surface Methodology (RSM) was then used to explore the design space and optimize the actuator geometry. The resulting designs increased stiffness in uncontrolled DoFs while preserving compliance in the active DoF. Experimental validation confirmed reduced out-of-plane deformation without sacrificing the required range of motion, improving actuator performance and supporting more expressive eye movements.

Index Terms—Soft robotics, tendon-driven actuators, finite element analysis, response surface methodology, social robots

I. INTRODUCTION

Social robots are increasingly used in education [1], health-care [2], and home assistance [3]. Among their interactive capabilities, eye movements play a key role in conveying emotions, attention, and intent, making them essential for natural human–robot interaction (HRI). For robots intended to interact with children, achieving expressive yet safe motion remains a central challenge.

Guided by the United Nations and UNICEF AI for Children policy [4], HARU was developed as a social robot that fosters educational and emotional engagement with children [5]. Recent iterations have progressively replaced rigid joints with compliant alternatives to improve safety, expressiveness, and adaptability during interaction (Fig. 1).

A current focus is the integration of soft actuators into HARU’s eye mechanism to provide additional degrees of freedom (DoFs). Tendon-driven soft actuators (TDCAs) are particularly attractive due to their inherent compliance and ability to generate smooth, organic motion. While previous studies have demonstrated the feasibility of tendon-driven soft joints, particularly for robotic necks [6], [7], [8], their optimization for robotic eye joints remains largely unexplored.

In the current HARU prototype [9], the first generation soft eye actuator exhibited unintended out-of-plane deformations

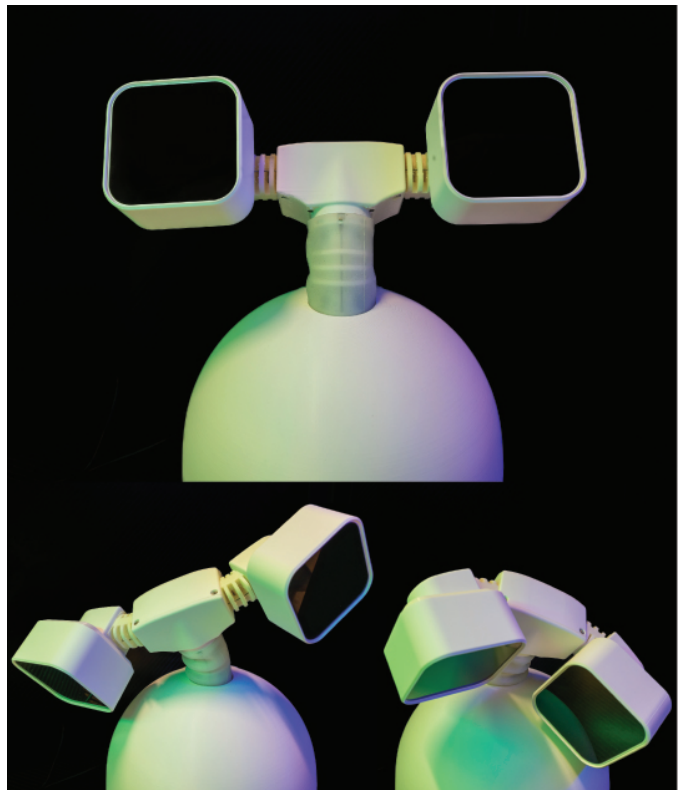


Fig. 1. Revised HARU prototype with soft joints in the head and eyes. This work focuses on optimizing the tendon-driven soft eye actuator to reduce out-of-plane deformation under load.

under the weight of the eye assembly, as illustrated in Fig. 2. These deformations produced downward eye poses that reduced gaze accuracy and naturalness, motivating the need for a structurally optimized design.

Addressing this challenge requires computational tools capable of capturing the nonlinear deformation of soft structures while enabling efficient design-space exploration. Finite Element Analysis (FEA) has been widely applied in soft robotics for modeling and design [10]–[15]. Beyond simulation, FEA has also supported topology, size, and shape optimization [16], [17]. However, only a limited number of studies [18]–[20] have combined FEA with Response Surface Methodology



Fig. 2. Definition of the active rotation ψ and out-of-plane rotations ϕ and θ of the eyes in the revised HARU prototype. For clarity and comparison purposes, the deformation under load is shown on one eye to better illustrate the challenge addressed through the soft joint optimization presented in this work.

(RSM) to reduce computational cost during optimization. This work extends that approach to the design of a tendon-driven soft eye actuator.

The key contributions of this work are: (i) a comparative analysis of three backbone cross-sectional geometries for a one-DoF tendon-driven soft eye actuator.; (ii) an optimization framework combining FEA and RSM to maximize stiffness in uncontrolled DoFs while preserving compliance in the active DoF; and (iii) experimental validation of the optimized designs, demonstrating reduced out-of-plane deformation while maintaining the required range of motion.

The rest of this article is structured as follows. Section II describes the robot's structure, focusing on the eye mechanism and optimization objectives. Section III presents an analytical comparison of the three cross-sections and the numerical simulation methods in ANSYS. Section IV outlines the RSM process and the selection of optimal backbone geometries. Section V covers actuator fabrication, the experimental setup, and testing. Section VI reports and discusses the simulation and experimental results. Finally, Section VII provides conclusions and directions for future work.

II. DESIGN METHODOLOGY

A. Eye Actuator Structure

The actuator used for HARU's eyes consists of three main components: a soft continuum core, a servomotor, and two tendon wires, as shown in Fig. 3. The core comprises two symmetrically arranged backbones connected by end caps and three equally spaced discs. The tendons pass through the inner end cap and discs before being anchored to the outer end cap. The inner and outer end caps are attached to the robot head and eye assembly, respectively.

The initial core design presented in [9] measured 28 mm in width and 40 mm in length, with rectangular backbones of height $h_b = 9.5$ mm and width $w_b = 5$ mm. Under the weight of the eye assembly, whose center of mass (CoM) is offset

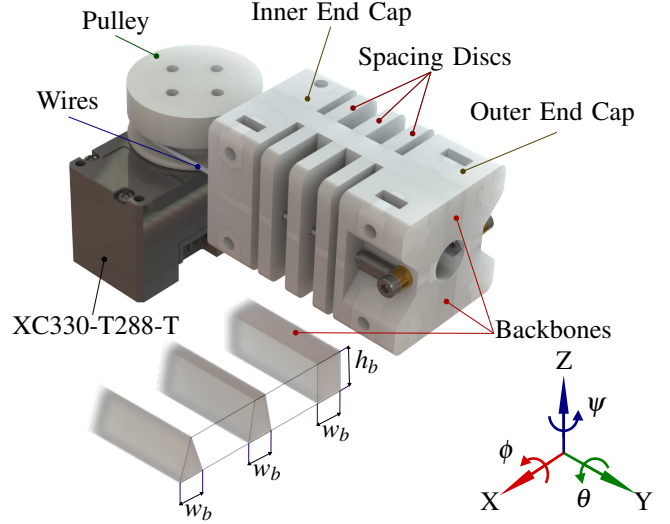


Fig. 3. Soft eye actuator showing the continuum core, tendon routing, and the three investigated backbone cross-sections. The design variables are the backbone width w_b and height h_b .

from the actuator, the core exhibited undesirable out-of-plane rotations ϕ and θ (Fig. 2), resulting in a downward eye pose.

To reduce these deformations while preserving compliance in the active DoF, three backbone cross-sectional geometries were investigated: rectangular, trapezoidal, and triangular. The design variables are the backbone width w_b and height h_b (Fig. 3). All geometries are symmetric about the horizontal plane, with the outer backbone surfaces located at a distance $h_c/2$ from the actuator center. In the trapezoidal design, the non-parallel sides intersect at the center of the core cross-section, leaving a central passage for routing cables to the eye assembly.

B. Optimization Problem

The design problem is formulated as a two-variable, two-objective optimization with one performance constraint. The

objectives are to minimize the out-of-plane angular deformations, bending ϕ and torsion θ , under the eye mass m , while ensuring an active rotation of at least $\psi = 40^\circ$ under a tendon force F . The design variables are the backbone width w_b and height h_b .

Two simulation studies were conducted:

- **Case Study A:** Minimize the load-induced deformations ϕ and θ under the operational load mg .
- **Case Study B:** Evaluate whether the actuator satisfies the performance constraint $\psi \geq 40^\circ$ under the actuation force F .

The eye assembly has a mass of approximately 240 g, and its center of mass was estimated in SolidWorks. Based on the actuator hardware reported in [9], the servomotor operating limit was set to 19.4% of stall torque, corresponding to a tendon force of approximately 17 N. The minimum yaw angle of 40° was selected to ensure the required range of expressive eye movements.

$$\begin{aligned} \min_{w_b, h_b} \quad & \{\theta(w_b, h_b, m), \phi(w_b, h_b, m)\} \\ \text{s.t.} \quad & \psi(w_b, h_b, F) \geq 40^\circ \\ & 5\text{mm} \leq w_b \leq 15\text{mm} \\ & 4\text{mm} \leq h_b \leq 10\text{mm} \end{aligned}$$

where ϕ and θ denote the out-of-plane rotations under the applied eye mass m , while ψ denotes the yaw rotation generated by a tendon force of $F = 17$ N.

III. MODELING

A. Analytical Inertia Comparison

The area moments of inertia I_X and I_Z , together with the torsional constant J_Y , provide a first-order estimate of the stiffness characteristics of the three backbone cross-sections. Here, I_X , J_Y , and I_Z correspond to bending about the X-axis (roll, ϕ), torsion about the Y-axis (pitch, θ), and bending about the Z-axis (yaw, ψ), respectively (Fig. 3). The optimization objectives can therefore be approximated by maximizing I_X and J_Y while constraining I_Z below a threshold I_Z^{const} .

Only the backbone structures were considered and the parallel-axis theorem was applied. All expressions are doubled to account for the mirrored backbone arrangement. Since no closed-form solution exists for non-circular sections, J_Y was obtained numerically through FEA.

1) Second Moment of Inertia on Roll axis:

Rectangular

$$I_X = 2 \left(\frac{w_b \cdot h_b^3}{12} + A \cdot d^2 \right) \quad (1)$$

Trapezoidal

$$I_X = 2 \left(\frac{h_b^3(w_i^2 + 4w_iw_b + w_b^2)}{36(w_i + w_b)} + A(d - C_Z)^2 \right) \quad (2)$$

Triangular

$$I_X = \frac{w_b h_b^3}{18} + 2A(d - C_Z)^2 \quad (3)$$

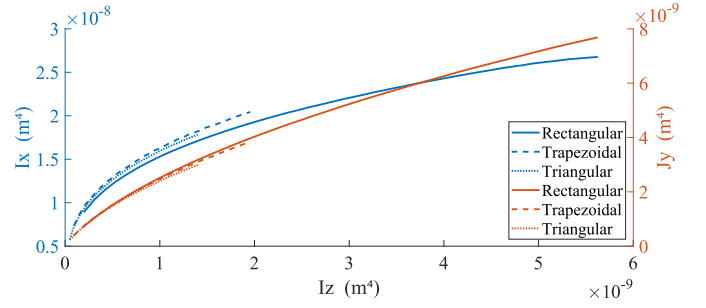


Fig. 4. Comparison of the maximum I_X and J_Y under constrained I_Z for rectangular, trapezoidal, and triangular cross-sections.

2) Second Moment of Inertia on Yaw axis:

Rectangular

$$I_Z = 2 \frac{h_b \cdot w_b^3}{12} \quad (4)$$

Trapezoidal

$$I_Z = 2h_b \frac{(w_i + w_b)(w_i^2 + w_b^2)}{48} \quad (5)$$

Triangular

$$I_Z = 2 \frac{h_b w_b^3}{48} \quad (6)$$

where A denotes the area of a single backbone cross-section, d is half the core height, and C_Z is the centroid location measured from the base of the trapezoidal or triangular section.

Fig. 4 shows the maximum achievable I_X and J_Y for a prescribed I_Z constraint. While all geometries exhibit similar torsional constants, the rectangular section provides the lowest I_X . In contrast, the trapezoidal and triangular geometries achieve substantially higher bending stiffness, motivating their further investigation through FEA.

B. Finite Element Modeling

1) **Material Modeling:** The soft cores were fabricated from Ninjaflex [9]. Following Hong et al. [21], the material was modeled using a third-order Ogden hyperelastic formulation. Parameters reported in [21] were adopted from ABAQUS and converted for use in ANSYS due to differences in the respective Ogden implementations. A comparative stress-strain analysis confirmed equivalent material responses, validating the conversion procedure.

2) **Wire Rope Modeling:** Directly modeling the individual strands of the tendon is computationally expensive. Therefore, the simplified segmented-cylinder approach proposed by Ding et al. [11] was adopted. The tendon was discretized only within the actuator core and connected through general joints allowing free rotation about the Z-axis.

A convergence study was performed by progressively increasing the number of segments. Six segments were selected for all simulations, as additional refinement changed the predicted yaw angle by less than 0.09%.

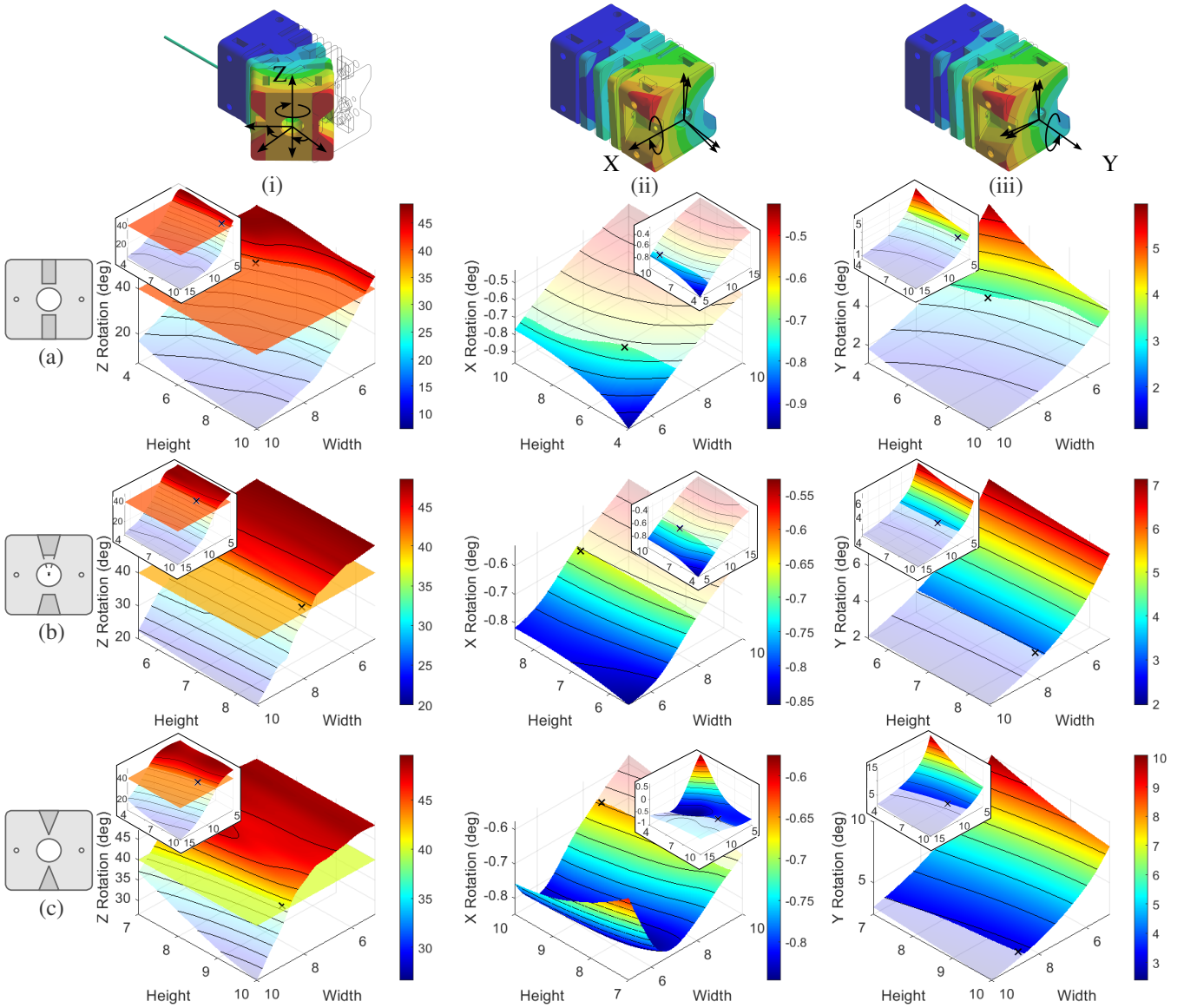


Fig. 5. Response surfaces for (i) yaw under tendon actuation and (ii)–(iii) roll and pitch under eye-mass loading for the rectangular, trapezoidal, and triangular backbone geometries. The semi-transparent plane in (i) indicates the constraint $\psi = 40^\circ$; infeasible regions are shown transparently in (ii) and (iii).

3) *Boundary Conditions*: Two simulation cases were considered. In both, the inner end cap was fully constrained while the remainder of the actuator was free to deform.

Case Study A: A load corresponding to the eye mass was applied at the center of mass estimated in SolidWorks. The resulting out-of-plane rotations ϕ and θ of the outer end cap were recorded.

Case Study B: Tendon actuation was modeled by applying a tensile force of 17 N through the wire. The resulting yaw rotation ψ was measured to evaluate operational performance.

IV. OPTIMIZATION RESULTS AND STRAIN ANALYSIS

The design space defined in Section II-B was explored using Response Surface Methodology (RSM). Sample points generated through a Central Composite Design (CCD) were

evaluated in ANSYS and used to construct surrogate models relating the design variables (w_b , h_b) to the actuator responses (ψ , ϕ , and θ).

Genetic Aggregation response surfaces achieved coefficients of determination $R^2 > 0.99$ for most responses and never below 0.94. Figure 5 shows the resulting response surfaces for yaw under tendon actuation and roll/pitch under eye-mass loading. The constraint $\psi \geq 40^\circ$ defines the feasible design region (opaque), within which the objective is to minimize ϕ and θ .

A Multi-Objective Genetic Algorithm (MOGA) was applied to identify Pareto-optimal solutions satisfying the yaw constraint. One candidate design was selected for each cross-sectional geometry and subsequently refined through a second RSM iteration. The resulting optimal dimensions are summa-

TABLE I
OPTIMIZED BACKBONE DIMENSIONS

Actuator	w_b (mm)	h_b (mm)
Initial	5.00	9.50
Rectangular	6.43	5.79
Trapezoidal	7.74	8.35
Triangular	8.66	9.87

TABLE II
MAXIMUM STRESS-STRAIN RESPONSES UNDER 17 N TENDON FORCE

Actuator	Stress (MPa)	Strain (m/m)
Rectangular	2.17	0.111
Trapezoidal	2.24	0.114
Triangular	2.68	0.136

rized in Table I. Relative to the initial design, the optimized rectangular backbone became wider and shorter, whereas the trapezoidal and triangular geometries converged to both larger widths and heights.

Maximum stress and strain under a 17 N tendon load were also evaluated (Table II). The triangular design exhibited approximately 20% higher strain than the rectangular and trapezoidal geometries, indicating a trade-off between increased out-of-plane stiffness and long-term durability.

V. EXPERIMENTAL STUDY

A. Experimental Setup

A setup replicating HARU's eye joint was developed to evaluate the actuator under Case A (weight load) and Case B (tendon actuation), as shown in Fig. 6. Eye orientation was measured using a BNO085 IMU mounted on the eye mockup and recorded through an Arduino Nano 33 IoT. For Case B, an XC330-T288-T servomotor controlled through a Dynamixel U2D2 interface actuated the tendon, while an inline LSB206 Futek load cell measured the applied force.

B. Actuator Fabrication

Baseline and optimized actuator cores were fabricated from Ninjabflex TPU using an FDM printer with a 0.4 mm nozzle, 0.15 mm layer height, 100% infill, and 240°C extrusion temperature. Three samples of each design were produced, with weight variation verified below 4.3%.

C. Experimental Procedures

Two experiments were performed for each of the twelve fabricated cores. For Case B, the IMU was zeroed in the neutral configuration and the servomotor was driven with a slow position ramp corresponding to a pulley velocity of 3.52 deg/s to approximate quasi-static loading. The resulting yaw angle ψ and tendon force were recorded simultaneously. For Case A, the eye assembly mass (240 g) was applied and the resulting deformation measured after stabilization to reduce creep effects. Before each trial, the IMU was re-zeroed using a fixed reference mount.

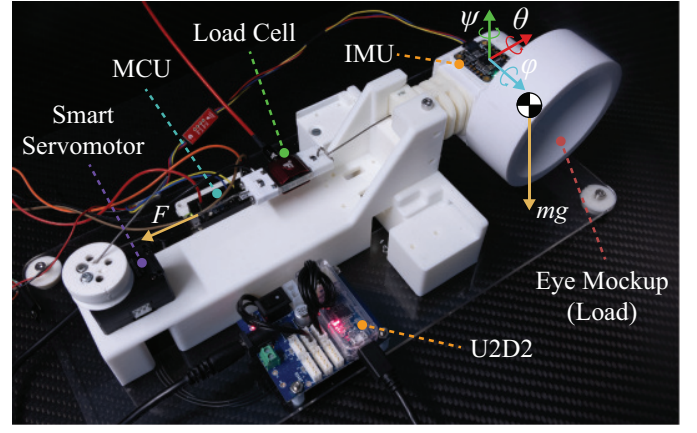


Fig. 6. Experimental setup used for Case A (weight load) and Case B (tendon actuation).

TABLE III
MEASURED ROLL AND PITCH ANGLES (°)

Actuator	Roll		Pitch	
	Exp	ANSYS	Exp	ANSYS
Initial	-1.48	-0.77	3.71	3.88
Rectangular	-0.89	-0.71	3.05	3.13
Trapezoidal	-0.92	-0.66	2.75	3.08
Triangular	-1.04	-0.65	2.74	3.06

VI. RESULTS & DISCUSSION

Both simulation and experimental results demonstrate that the optimized backbones reduce unwanted out-of-plane deformation while preserving the required yaw motion. All optimized designs achieved rotations exceeding 40° with tendon loads below 26.2% of the servomotor stall torque. Relative to the baseline actuator, roll and pitch deformations were reduced by approximately 29.5% and 18.9%, respectively.

A. Reduction in Out-of-Plane Deformations

Table III summarizes the measured roll and pitch deformations. All optimized geometries reduced both roll and pitch relative to the baseline actuator, confirming increased stiffness in the uncontrolled DoFs. The largest reductions were observed in pitch, where the optimized designs lowered deformation from 3.71° to approximately 2.75°. Differences among the optimized geometries were small, with maximum deviations of only 0.15° in roll and 0.31° in pitch. Consequently, all three designs effectively eliminated the unintended downward eye pose observed in the baseline configuration.

B. Force Efficiency in Controlled Motion

The tendon forces required to achieve 40° yaw are reported in Table IV. Although the optimized designs required slightly higher forces than the baseline actuator, all remained within the intended operating range, corresponding to less than 26% of the servomotor stall torque. The maximum variation among optimized geometries was only 2.5%, indicating that the increased out-of-plane stiffness was achieved with minimal impact on actuation efficiency.

TABLE IV
TENDON FORCE REQUIRED FOR 40° YAW

Actuator	Exp (N)	ANSYS (N)
Initial	19.0	—
Rectangular	22.9	17.0
Trapezoidal	22.9	17.0
Triangular	22.4	17.0

C. Simulation Accuracy and Experimental Validation

The finite element model captured the overall actuator behavior with good accuracy while highlighting physical effects not represented in the simulations. Experiments required 24–26% higher tendon forces to achieve 40° yaw than predicted by ANSYS, likely due to tendon friction, connector compliance, and material variability.

Pitch deformation showed the closest agreement between simulation and experiment, with deviations of 3–12%. Roll deformation exhibited larger relative errors, particularly for the baseline design, although the maximum absolute discrepancy remained below 0.39°. Given the small magnitude of these differences, their effect on eye orientation is negligible.

The overall results validate the simulation framework's ability to predict performance trends and relative improvements across designs, while highlighting the importance of accounting for real-world effects in soft-actuator design.

VII. CONCLUSION

This work presented an FEA–RSM framework for the structural optimization of tendon-driven soft eye actuators for the social robot HARU. Three backbone cross-sectional geometries were evaluated and optimized with respect to out-of-plane stiffness while maintaining the required actuation range. Experimental results showed that the optimized designs reduced roll and pitch deformations by approximately 30% and 18%, respectively, while achieving yaw rotations exceeding 40° within the operating limits of the servomotor. The small performance differences among the optimized geometries indicate that the proposed methodology yields robust solutions across multiple backbone configurations. These results demonstrate the effectiveness of combining finite element analysis with response surface optimization for the design of compliant robotic joints and contribute to improving the naturalness and reliability of eye motion in social robots. Future work will focus on improved TPU material characterization, multi-material actuator designs, and the extension of the framework to other compliant joints in HARU.

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