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NUMERICAL APPROACH FOR ANALYZING 3D-PRINTED FINRAY SOFT GRIPPERS WITH ARTICULATED CROSS BEAMS

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Abstract: *Soft robotic grippers inspired by the Fin Ray Effect have gained attention due to their ability to gently interact with objects. This study presents the design and 2D numerical analysis of a three-jaw 3D-printed soft gripper that includes articulated cross-beams. Opposed to existing simulation methodologies, the work focuses on computational efficiency and result accuracy by employing simplifying assumptions. The assembly was fabricated by using ABS via material extrusion. Validation against experimental data proved angular deformation deviations below 5%, confirming the accuracy of the simulation model. The gripper effectively adapts to the geometry of the objects while maintaining structural resilience. These findings highlight the efficiency and accuracy of the numerical approach, supporting rapid design iterations.*

Keywords: *soft-gripper, finray design, transient structural analysis, 3D-printing, deformation.*

1. INTRODUCTION

1.1 Background and motivation

The research field of gripping systems is usually focused on improving the classic solutions to enhance their reliability, durability, and overall performance [1]. Grippers, such as prismatic jaws with “V” profiles for centering pipes, or straight jaws for cuboid parts, are highly effective for repetitive tasks involving objects with predictable shapes [2]. However, these solutions have limitations when required to handle objects with varying shapes, dimensions, and material properties [3]. In such applications, especially for industries where products often have irregular geometries and are prone to deformations or breakage under excessive force, soft, multifunctional, and modular gripping systems emerged as valuable alternatives [4]. These grippers can exploit the flexibility and compliance provided by their material and design in order to conform to the shape of the object being handled, thus reducing the risk of damage, while improving grip adaptability. This characteristic makes them especially suitable for applications in domains such as food handling, medical robotics, and automated assembly lines where safe, gentle, and reliable object interaction is mandatory [5, 6]. An example of such soft gripper is based on a finray structure, inspired by the natural mechanics of fish fins (Fin Ray Effect®), which includes a triangular profile reinforced with cross beams (also known as links or ribs) between the active and back faces of the jaw, enabling their conformance to a wide variety of shapes and evenly distributing the load [7]. By adjusting parameters such as material, thickness, design of cross beams between faces, and actuation methods, designers can customize the gripper’s behavior by targeting a balance between stiffness and flexibility.

While most finray grippers have two jaws and use parallel actuation mechanisms, an alternative actuation method and coupling system was explored in this study for a solution with three finray jaws, evenly distributed across 360°. The gripper includes dovetail and gear coupling mechanism for integration with a rotary actuation system, advancing the state-of-the-art by combining flexibility, adaptability, and compact design. Another design goal was to 3D print the jaws as a single assembly, thus eliminating the need for manual assembly. The gripper was manufactured from acrylonitrile butadiene styrene (ABS) using material extrusion process (MEX). While thermoplastic polyurethane (TPU) is commonly used for soft grippers due to this material flexibility and adaptability, it has limitations like excessive compliance, lower wear resistance, and limited stiffness range. These can restrict its use in applications requiring controlled deformation and enhanced structural stability. ABS addresses these challenges providing a balance between rigidity and flexibility, being a better choice when adaptability, effective load distribution and durability are required.

Designing and optimizing finray grippers requires understanding their structural behavior, which is influenced by the material properties, the geometry of the cross-beams and their actuation mechanisms. Due to the nonlinear behavior of flexible structures, Finite Element Analysis (FEA) is a central tool for predicting mechanical response, stress distribution, and performance prior to physical prototyping. FEA helps evaluating the material choices, optimizing cross-beam configurations, and analyzing contact interactions for ensuring that the gripper balances flexibility and load-bearing capacity. Additionally, numerical simulations reduce development time and costs by identifying potential failure points early in the design process. In this context, this study proposes 2D transient structural method for simulating the deformation of the gripper's jaws around an object, addressing a gap identified in the literature. Sections 2.1 and 2.2 outlines the key aspects of the gripper's design and MEX process, while Sections 2.3 presents FEM simulation model preparation stages as well as the simplified assumptions employed for reducing the computational costs. The validation process and results are detailed in Section 3, followed by conclusions and future research directions in Section 4.

1.2 Literature review

Literature was reviewed to identify FEM based approaches applied to 3D-printed finray grippers made from various materials, with applications ranging from industrial automation to medical and food handling [4-5]. The analyzed papers present the design, simulation, and experimental validation of soft robotic grippers, particularly focusing on finray effect and similar adaptive structures. FEA was used as a tool for assessing the structural behavior, optimizing designs, and improving gripper performance for different applications and under different operating conditions.

The field of soft grippers, particularly those utilizing flexible materials and innovative design approaches, has seen significant advancements in recent years. Researchers have focused on optimizing various aspects of gripper performance, such as load capacity, grasp stability, adaptability, and material efficiency, using novel materials and computational methods. In this regard, Müller et al. (2020) proposed a simulation-based design approach for heavy-duty grippers intended for payloads larger than 10 kg. TPU-95A (NinjaFlex) was employed for 3D printing. An experimental setup was developed for load testing, focusing on the load capacity and deformation of a gripper comprising two jaws, 10 ribs, and a 1 mm fin wall thickness [8]. Similarly, Deng et al. (2021) studied the optimization of finger geometry using pseudo-kinematics and task constraints, focusing on grasp stability and adaptability. The use of TPU-95A in their experimental testing was aimed to improve grasp quality functions by introducing task-specific parameters to optimize the design of soft grippers [9].

De Barrie et al. (2021) integrated FEM and deep learning techniques to predict contact forces and stress distribution using external camera images. This study showed the integration of real-time feedback for force prediction, improving the accuracy of soft TPU gripper performance [10].

Srinivas et al. (2024) focused on topology optimization to reduce material usage while maintaining grasping efficiency. TPU-95A was used for 3D printing. A robotic arm setup was included for experimental validation [11].

Kitamura et al. (2023) investigated the contact forces and deformations through a combination of FEA and experimental work, using flexible materials. Their study provided insight into the influence of rib angles on gripper performance, with a focus on improving contact force and deformation behavior [12].

In terms of material selection, Chen et al. (2023) explored the combination of dimethicone elastomer with rigid ABS beams for electrically controlled adhesion in soft grippers. The research focused on the bending and contact area behavior with objects for enhancing the shape-adaptive mechanics [13]. Yao et al. (2023) used parametric models and FEM to investigate the effects of internal structures on adaptability and grasping force. The experimental testing of TPU-95A with different internal structures, including branched and cross designs, provided comparative insights into the force response generated by each structure [14].

Emerson et al. (2023) focused on optimizing rib angles and geometry for enhanced grasping performance. The research involved experimental validation by deformation tests, emphasizing shape adaptation and stability in gripping circular objects. Another objective of the study was to explore layer jamming as a method to generate force and enhance grip stability [15].

Shan et al. (2023) analyzed the modeling and performance of parallel finray grippers. By conducting tests with cylindrical objects, the study highlighted the influence of rib configurations on grip strength and contact forces, contributing to the modeling of soft robotic fingers based on the finray effect [16]. Finally, Crooks et al. (2023) used modeling and experimental validation to optimize gripper design for improved deformation and grip strength. By using materials such as NinjaFlex and Veroclear, the work focused on enhancing contact area, tip displacement, and grip stability, achieving asymmetries in the cross beams and thus, improve bending around objects [17].

These studies collectively highlight the diverse approaches and innovations in soft gripper design, including material optimization, geometry adjustments, deep learning integration, and structural optimization, all contributing to advancing the performance and efficiency of soft robotic systems. Research also included experimental validation, integrating simulations with physical testing, while the validation of the numerical analysis varied from load testing to dynamic grasping experiments and force measurement using sensors. Most studies primarily relied on passive compliance, only a few exploring motor-driven and layer jamming methods. No data of durability assessment were found.

Among the reviewed studies, Deng et al. [9] used both 2D and 3D transient structural analyses, mentioning that 3D analysis is more accurate but computationally expensive, while 2D is faster. For rapid design iterations, 2D transient structural analysis [9] and kinetostatic modeling [16] can provide efficient solutions by reducing computational complexity while maintaining adequate accuracy for completing initial optimization studies. On the other hand, topology optimization [11] can enhance the material efficiency by reducing mass while maintaining structural integrity, making it useful for applications where weight constraints are imposed. Nonlinear static FEA was also used in [2] by incorporating advanced material models, such as hyperelasticity, to predict deformation behavior under real-world conditions.

ANSYS was the most commonly used solver for TPU-based studies. Chen et al. [13] employed ABAQUS due to its better handling of nonlinear hyperelastic materials. De Barrie et al. [10] innovated by using FEA-generated training data for developing a deep learning force prediction model.

Optimizing the gripper geometry and material properties to improve load distribution and adaptability are two of the objectives aimed in studies such as [8], in which FEA was used to evaluate structural integrity under heavy loads, or in [11], where finray jaws were topological optimized with FEA to reduce the gripper's weight while maintaining high grasping efficiency. FEA was also used to simulate the grippers' response to contact forces and deformations [12].

The contact force studies used FEA to assess how crossbeam arrangements in finray structures affect grasping performance, while studies on different internal structures evaluate adaptability and force responses [13, 14]. Rib angle optimization used FEA to improve force distribution and reduce object slippage [15], while the infill pattern study examines how internal structures impact flexibility and strength, identifying optimal designs with FEA.

Common challenges across all studies include material anisotropy from 3D printing, which influences the simulation accuracy, the need for significant computational resources due to nonlinear material models and complex geometries, and ensuring simulated results align with physical performance.

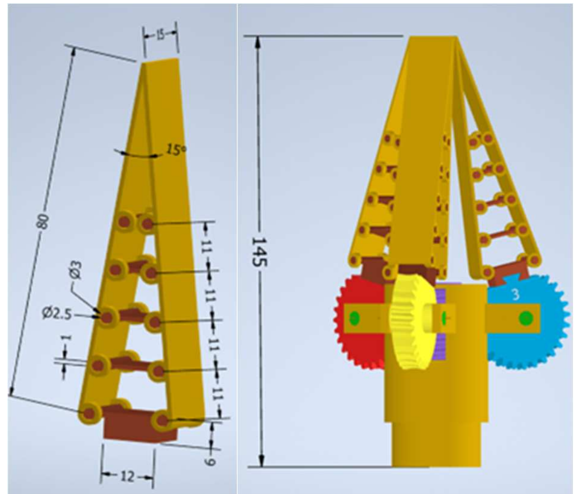
The current study introduces an enhanced FEM simulation model for accurately capturing jaw deformation in finray effect soft grippers during object manipulation. Several simplified assumptions were included to enhance computational efficiency. Two material models are employed: linear elastic and a plasticity model based on bilinear hardening. While 3D-printed polymers typically exhibit anisotropic behavior due to the layer-by-layer deposition process and infill structure, the use of a gyroid pattern at 100% infill density justifies these assumptions. Experimental and numerical studies have shown that gyroid infills exhibit near-isotropic behavior [18], offering uniform strength and resistance in all directions, unlike grid or honeycomb patterns.

A 2D plane stress approach was employed to simplify the mesh generation process, at the same time reducing the number of equations to solve. Rib motion is constrained by using Multi-Point Constraint (MPC) elements, minimizing the complexity of frictional contact modeling. Cross ribs were replaced with equivalent stiffness springs to replicate their kinematic behavior. Time step control was optimized to ensure efficient simulations without compromising essential details.

2. MATERIALS AND METHODS

2.1 Soft gripper design

The proposed gripper (Fig.1) introduces several novel design features that differentiate it from existing finray grippers, enhancing both adaptability and modularity. The first key aspect is its three-jaw configuration, the reviewed literature and online data indicating that two-jaw arrangements are predominant, which allows for more uniform force distribution around the object, improving grip stability and enabling the effective handling of complex or irregularly shaped objects. While a three-jaw finray gripper has been described in [19], it was designed as a single-piece structure without articulated joints, limiting its adaptability.



(a) (b)

Fig.1. Design of a finray jaw with dimensions (a); whole gripper (b) (dimensions in mm)

The second novelty is represented by the articulated joints in combination with inclined cross-beams, which significantly improves adaptability. Crooks et al. [17] showed by numerical and experimental studies that ribs inclined toward the base of the jaw enhance bending of the contact surface, improving conformity to the gripped object. Based on this finding, the proposed design incorporates five cross-beams in each of the three concentric finray jaws, linked to the faces through articulated joints that enable dynamic adaptation to various object shapes and sizes.

This configuration is designed to provide superior surface conformity compared to static rib designs used in existing grippers. Four cross-beams are articulated with the gripper faces to enhance adaptability, while the fifth beam at the base incorporates a dovetail shape, allowing secure actuator assembly and easy replacement, thereby improving modularity and maintainability. A clearance of 0.5 mm in the joints was set in order to facilitate a smooth relative motion of the crossbeam.

Another new aspect is integrating the actuation system into a single 3D-printed assembly, featuring a worm gear mechanism. This design ensures precise alignment, reduces costs, simplifies assembly, and leverages the self-locking property of worm gears for energyefficient grip retention. The gripper prototype uses a 5V motor with a 127:1 gear reducer, transmitting motion via a worm shaft and three worm wheels, with hexagonal support shafts to minimize friction.

2.2 Soft gripper 3D printing by MEX

Each jaw was directly 3D-printed as a single assembly using 100% infill density. A Tree support structure was used to facilitate easy removal of supports after fabrication. The thickness of a layer was set to 0.15 mm, while the wall thickness was set to 1 mm considering the dimensions of the finray structure. Bed temperature was set cu 85°C, the extrusion temperature to 250°C for the first layer, then 235°C for the other layers. The printing speed was set to 60 mm/s, and the build room temperature was 36°C. The slicing was performed in Ultimaker Cura with the finray oriented horizontally. 3D printing was carried out on a Ultimaker 3 3D printer. ABS filament (Ultimaker, NH) was used due to its strength and durability. A brim adhesion was employed to the build platform, given the tendency of ABS to contract and deform. ABS was selected for its balance between stiffness and flexibility, as insuring the structural integrity of the gripper during functioning is mandatory. Also, it was shown [20] that ABS maintain its mechanical properties when disinfected and sterilized, which is an important aspect for soft grippers used in food industry.

2.3 FEA of the soft gripper using a 2D transient structural method

ANSYS Workbench release 2022 R1 was employed for completing the numerical study. The material properties were depicted from the MATWEB library in table 1 [21]. The material properties are similar with the properties of Ultimaker ABS filament as reported by producers.

Table 1.

Materials properties [21]

ABS	**Nylon**
E (Young's modulus) = 2040 MPa	E= 2000 MPa
ν (Poisson's coefficient) = 0.37	*ν* = 0.4
σ_{s0} (Yield strength) = 26.84 MPa	σ_{s0} = 100 MPa
E_{TAN} (Tangent modulus)= 1300 MPa	E_{TAN}=1000 MPa

Two simplification entities: MPC184 and COMBIN14 as well as the Plane Stress theory are employed as prerequisites.

Plane-stress theory applies to plates or thin bodies where the stress tensor, typically a 3x3 matrix, reduces to a 2x2 matrix as the stress component in one spatial direction is null. The general form of the stress tensor for a 3D element is:

$$\begin{bmatrix} \sigma_x & t_{xy} & t_{xz} \\ t_{yx} & \sigma_y & t_{yz} \\ t_{zx} & t_{zy} & \sigma_z \end{bmatrix}. \quad (1)$$

When the element is realigned with its faces normal to the global axes, the shear stresses become null, simplifying the tensor to:

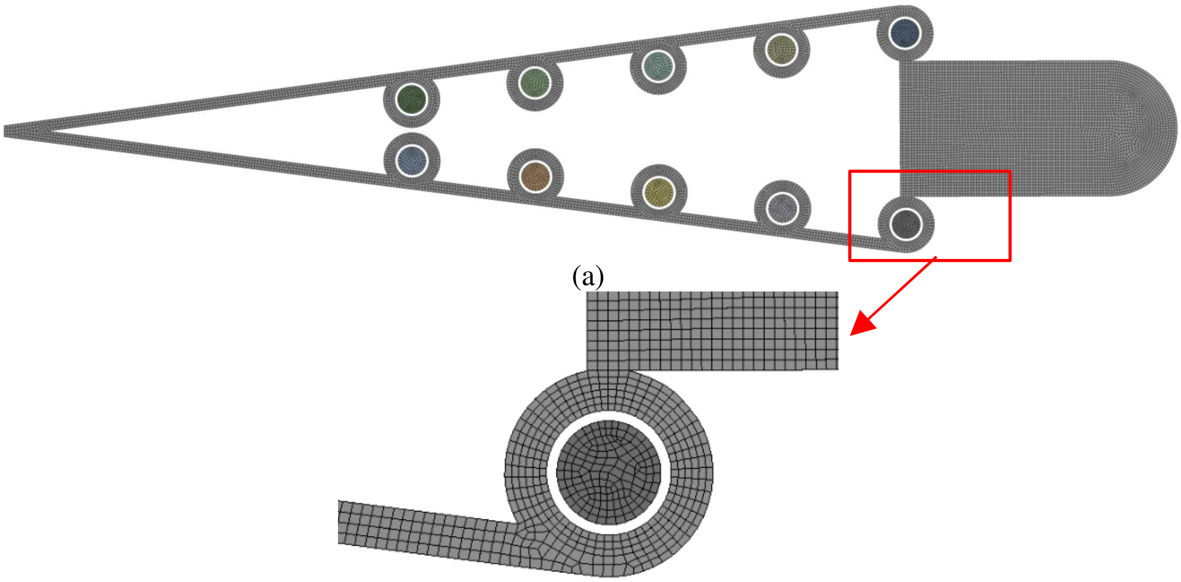
$$\begin{bmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{bmatrix}. \quad (2)$$

To obtain the final form of the tensor which respects the plane stress theory, it is require imposing the σ_z to be null.

MPC 184 [22] is a joint element used to simulate a 3D joint by bonding multiple nodes to a parent node with rigid beams. This MPC allows the independent node to rotate perpendicular to the XY plane while limiting its translations through the child nodes, which resist displacement.

COMBIN 14 [23] is a 2D string element that uses longitudinal stiffness (spring constant) to determine the response force when one end is displaced. It replaces cross-ribs in the 3D model by capturing their equivalent stiffness.

The first step to obtain the 2D simplified analysis was to define a planar representation of the jaw assembly. This continuous domain is meshed with PLANE182 elements (Fig.2).



(a)

(b)

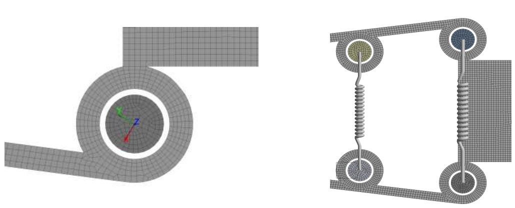
Fig.2. Details of the mesh – (a) Global view and (b) Detailed view

Afterwards, individual groups of Remote Points are defined as rigid constraint equations for defining both the MPC 184 as well as the COMBIN14 elements. Along with the remote points, there is also a need for a datum system to be attached to each MPC's rotation axis.

A summary of the user defined commands is depicted bellow:

```
et,_jid,184 ! Set element type to MPC 184
keyo,_jid,1,6 ! Set behavior as revolute joint
keyo,_jid,4,1 ! Z axis is the revolute axis
```

Between the centers of each joint a spring (COMBIN14) had to be created to mimic the action of the ribs (Fig.3).



(a) (b)

Fig.3. Details of the joint and spring element definition – (a) revolute joint coordinate system and (b) spring connection between the center nodes of the remote points

The k parameter of each spring was calculated according to the cross-section of the rib. Mesh generation was completed by using a 0.25 mm element size. A total of 10657 nodes and 3048 elements were generated.

The following parameters were specified for automatic time step control during the solution process: initial time step: 1E-5 s; minimum time step: 1E-7 s; maximum time step: 0.5 s.

3. RESULTS AND DISCUSSIONS

3.1 FEA results

The solving process completed successfully, with a total of 3139 iterations carried out to capture 1 second of physical time, and the timestep for which the simulation was stable for most of the time was 0.0025 s.

Figure 4 presents the time vs. equivalent Von-Mises stress graph. The most critical value occurs at 88% of the simulation cycle, having a magnitude of 19.751 MPa. There is no risk of structural integrity loss given the fact that the minimum tensile yield strength of both materials employed is 26.84 MPa. Thus, the calculated safety factor of 1.35 is found within the recommended range of 1.2 to 2 [24].

Figure 5 shows the fringe plot of the Von Mises stress derrived for the critical time step. The peak stress gradients are concentrated at the base of the jaw, where it connects to the housing. The stress values are gradually decreasing along the length of the jaw and towards the articulated beams, with minimal stress observed at the tips of the jaws.

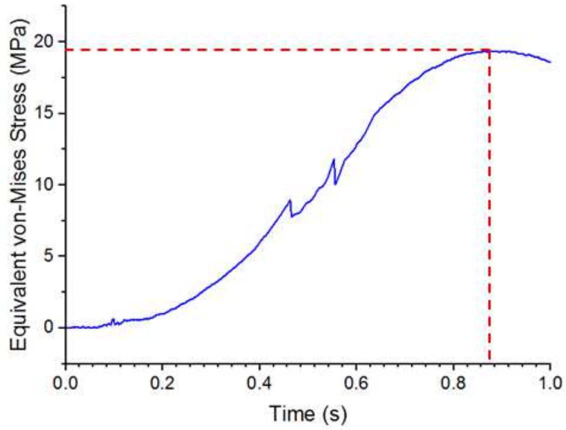


Fig.4. Equivalent stress graph with maximum stress of 19.751 MPa occuring at 88% of the simulation cycle

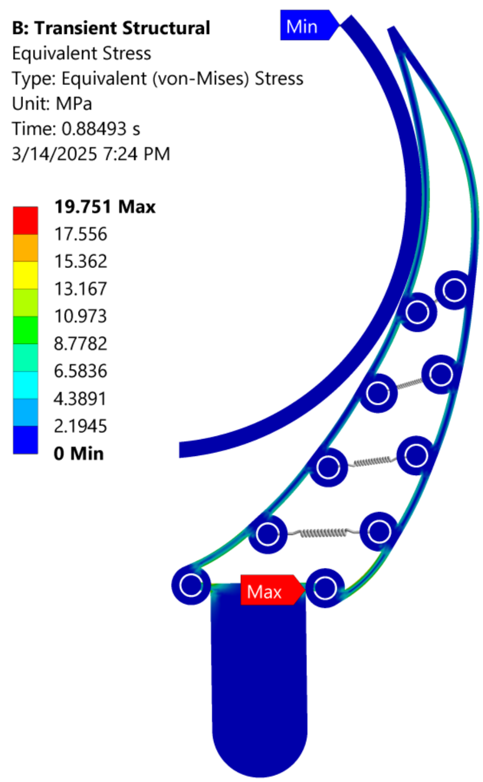


Fig.5. Equivalent von Mises stress fringe plot for the most critical time step

The maximum value of the equivalent elastic strain is 0.96%, occurring near the articulated joints in the midsection of the jaw (Fig.6).

Strain distribution proves that the jaw will deform so that to adapt to the object's shape during gripping. The strain is decreasing towards the base and the jaw tip, proving that the articulated design is effective in controlling the bending without excessive local deformation.

3.2 Experimental validation

The validation of the FEA model was performed by comparing the simulated deformations of the FinRay structure with the real deformations observed in images acquired while gripping a spherical object (65 mm diameter – tennis ball) (Fig. 7).

The rib angles were compared by using ImageJ software (Fig.8). Measurements were completed starting from the base (α_1) to the top ($\alpha 4$) of the jaw with each vertex being the center of each joint on the left side of the jaw. The three points are placed using the on screen pointer and the final list is exported as a .csv file. Table 2 depicts the resulting percent error for the calculated angles.

The numerically derived angles were calculated by employing the nodal coordinates of the displaced remote point centroids occurring at the final step. The inverse cosine (arccos) of the result from the dot product was employed to achieve this objective. The percentage error below 5% for all calculated angles confirms the accuracy of the simulation model.

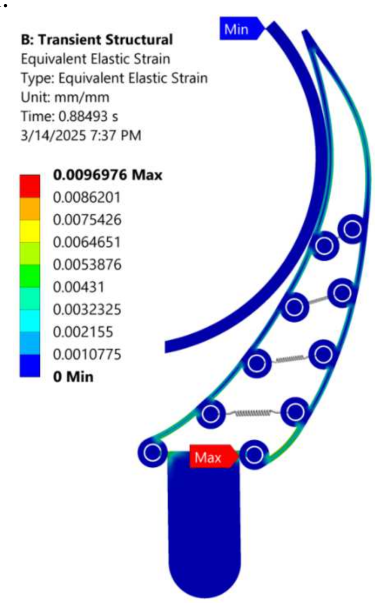
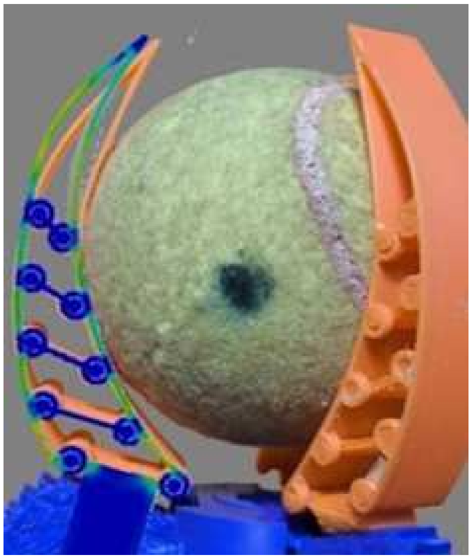
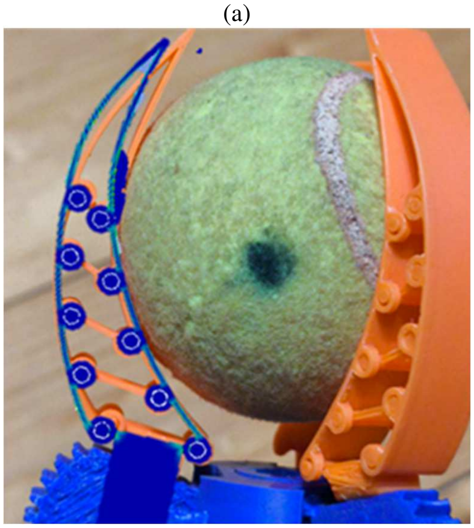


Fig.6. Equivalent Elastic Strain fringe plot for the most critical time step



(a)



(b)

Fig.7. Image showing the overlapped simulation / experiment results for 3D (a) and 2D (b)

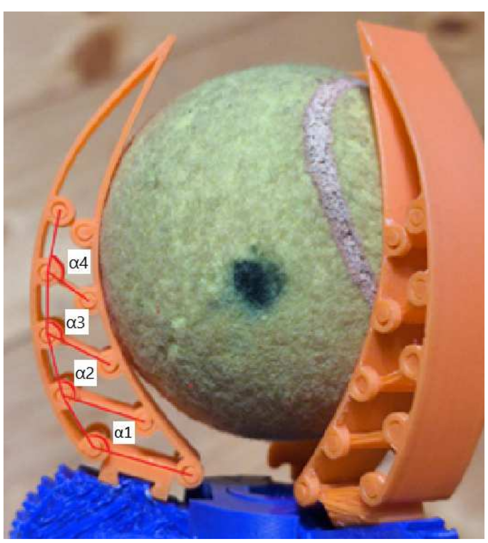


Fig.8. Image of a jaw deformation/cross beams angles

Table 2.

Percent error for calculated angles.

Angle	Experimental	Numerical	Percentage error (%)
α_1	130.932	125.006	4.74%
α_2	118.49	118.283	0.17%
α_3	116.362	116.565	0.17%
α_4	112.178	112.3	0.10%

4. CONCLUSIONS

This study presented a novel design for a 3D-printed soft gripper based on the Fin Ray Effect, featuring a three-jaw configuration that enhances adaptability and modularity. The design enables efficient handling of objects with varying shapes and sizes while balancing stiffness and flexibility. Articulated cross-beams improve surface adaptation to objects. A 2D transient structural analysis was used to reduce computational complexity while maintaining accuracy, with simplified assumptions for modeling ribs. ABS was selected for its durability and optimal balance between rigidity and flexibility, making it suitable for controlled deformation applications. FEA simulations showed that the gripper can adapt to objects without excessive deformation, with a safety factor of 1.35 ensuring structural integrity. Experimental validation confirmed the model's accuracy, with less than 5% deviation in angular measurements. Future work may focus on optimizing the gripper for different materials, enhancing the actuation system, and further reducing computational costs.

Despite its widespread use in structural components, ABS presents some material limitations such as sensitivity to warping, often requiring a heated bed and/or controlled 3D printing environment, which impact its uses for specific applications. Moreover, ABS material is known to exhibit brittle failure under repeated stress loading, and this can restrict its use in the gripper scenario. Therefore, further investigations are aimed on evaluating other materials like nylon, TPU-based blends, or fiber-reinforced polymers, to assess their potential for improving adaptability mechanical strength, and printability, while keeping the functional requirements of the soft gripper.

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Abordare numerică pentru analiza sistemelor de prehensiune cu bacuri flexibile integrând nervuri articulate

Sistemele de prehensiune cu bacuri flexibile au atras atenția datorită capacității lor de a manipula obiecte fragile. Această lucrare prezintă proiectarea și analiza numerică 2D a unui astfel de sistem, care include nervuri articulate. Spre deosebire de metodologiile existente de simulare, lucrarea se concentrează pe eficiența computațională și acuratețea rezultatelor prin utilizarea unor ipoteze simplificatoare. Ansamblul a fost fabricat utilizând ABS prin printare 3D. Validarea față de datele experimentale a demonstrat abateri de deplasare unghiulară sub 5%, confirmând acuratețea modelului de simulare. Ansamblul se adaptează eficient la geometria obiectelor, menținând în același timp integritatea structurală. Aceste contribuții evidențiază eficiența și acuratețea abordării numerice, susținând iterațiile rapide de design.

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