Bio-Inspired Design of a 24-DoF, Fully Actuated Robotic Gripper with Series Elastic Actuators for Soft Grasping and Feedback-Controlled Motion

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***Abstract*— The development of robotic grippers that mimic the configuration and compliance of the human hand remains a significant challenge in robotics. This work presents a bio-inspired design of a 24-degrees-of-freedom (DoF) fully actuated robotic gripper that is integrated with Series Elastic Actuators (SEAs) to achieve actuator level compliance. The gripper is designed to replicate anthropomorphic finger articulation while enabling soft grasping capabilities for delicate object manipulation.**

The novelty of design is in simplification of sensor requirements as only potentiometer-r-based feedback is employed for joint-level position and force control. Additionally, the scheme allows bulk of sensors and actuators to be positioned at suitable distant location so as to avoid clutter at joint locations, considering form factor of human hand.

The proposed, SEA based implementation scheme provides advantage in adaptability, safety, and versatility compared to rigidly actuated counterparts.

Results highlight the potential of SEA-based fully actuated grippers for bridging the gap between compliant actuation and bio-inspired robotic design.

Keywords*— *Series Elastic Actuators, Robotic gripper, 24-Degrees of Freedom, Dynamic simulations for Robotic gripper, fully actuated grippers, soft grasp, potentiometer, position feedback.

I. Introduction

The development of robotic grippers that mimic the functionality of the human hand has long been a central goal in humanoid robotics. This study began with literature review, that enabled the identification of key design parameters and the formulation of quantitative performance targets. Based on these insights, we defined a systematic approach that included the selection of suitable actuation technologies, formulation of implementation strategies, and iterative design through computer-aided modelling, simulation-based verification, and prototyping.

The envisioned application of the proposed gripper is as an end-effector for the manipulator arm of a humanoid robotic platform, where control signals and power will be supplied from the main robotic body. As the gripper is designed to replicate the functional characteristics of the human hand, it is expected to perform tasks like human such as gripping, grasping, and manipulating objects of diverse shapes and sizes. Importantly, the design ensures that objects can be held securely even in the event of power interruptions, thereby enhancing reliability and safety.

A critical feature of the gripper is the incorporation of compliance at each actuator, achieved through Series Elastic Actuators (SEAs). This compliance enables energy storage, safe interaction in human-centric environments, and effective handling of irregularly shaped objects. In addition, the system provides joint-level position sensing and force feedback. Compliant control is essential for robotic systems intended to operate alongside humans, whether in collaborative tasks, tool handling, or operating human-designed equipment.

To the best of our knowledge, this is the first implementation of series elastic actuation in a 24-DoF fully actuated robotic gripper that combines potentiometer-based compliant control to achieve bio-inspired soft grasping. This paper also situates the proposed design within the broader landscape of robotic hand research.

A. *1.1. Structure of human musculo-skeletal system*

The human hand derives its motion from a complex musculoskeletal structure composed of muscles, tendons, and bones. Hand muscles are categorized into two groups: extrinsic and intrinsic. Extrinsic muscles, located in the forearm, include the long flexors and extensors that actuate finger movements through tendinous connections. Intrinsic muscles, positioned within the hand, provide fine motion and contribute to dexterity [1, 2].

Each finger is actuated by two long flexors: the deep flexor, attached to the distal phalanx, and the superficial flexor, attached to the middle phalanx. These muscles facilitate finger bending. The thumb contains a long and a short flexor in thenar group, along with additional muscles that enable opposition, a motion essential for grasping. Extensors, located on the dorsal side of the forearm, are connected through a coordinated tendon network that forms the extensor mechanism, whose primary role is to extend the phalanges [2]. References [1–3] were particularly useful in understanding this anatomy and guided the development of the CAD model.

B. *1.2. General nomenclature followed for human hand*

i. Distal phalanx – the fingertip segment
ii. Intermediate phalanx – the middle segment
iii. Proximal phalanx – the segment closest to the palm
iv. Metacarpal phalanx – bones within the palm (metacarpal link)
v. Fixed base – the wrist joint, where the metacarpals are hinged

1.3. Types of grasps

The human hand primarily performs two categories of grasps [4]: power grip and precision grip (Fig 1). Power grip emphasizes maximum payload capacity, while precision grip enables dexterity and fine control. In this work, power grip is adopted as the primary design target, with precision grasping (e.g., handling fragile objects like eggs or deformable items) defined as a secondary goal.

1.4. Review of Anthropomorphic Robotic Grippers

A number of anthropomorphic robotic hands are reviewed in literature [5]. Prominent examples include the Shadow Hand [4], Robonaut-2 Hand [6], HRI Hand [7], and DLR Hand-II [8]. The following general observations were made:

i. Maximum reported DoF = 24
ii. Most designs used extrinsically placed actuators
iii. Active joints were often fewer than the hand's natural DoFs
iv. Majority of designs were under-actuated (one actuator driving multiple joints)
v. Tendon-driven actuation was the most common mechanism
vi. Sensors frequently employed included tendon tension, position, and tactile sensors
vii. Additive manufacturing has increased the feasibility of producing advanced gripper
viii. Recent works have employed additive manufacturing based single-step manufacturing approaches for fully functional mechanisms [9]

1.5. Key Inferences for the Present Work

Insights from prior studies [10,11] were instrumental in defining the objectives of this project. The main inferences are:

i. Development of anthropomorphic gripper with 24-DoF

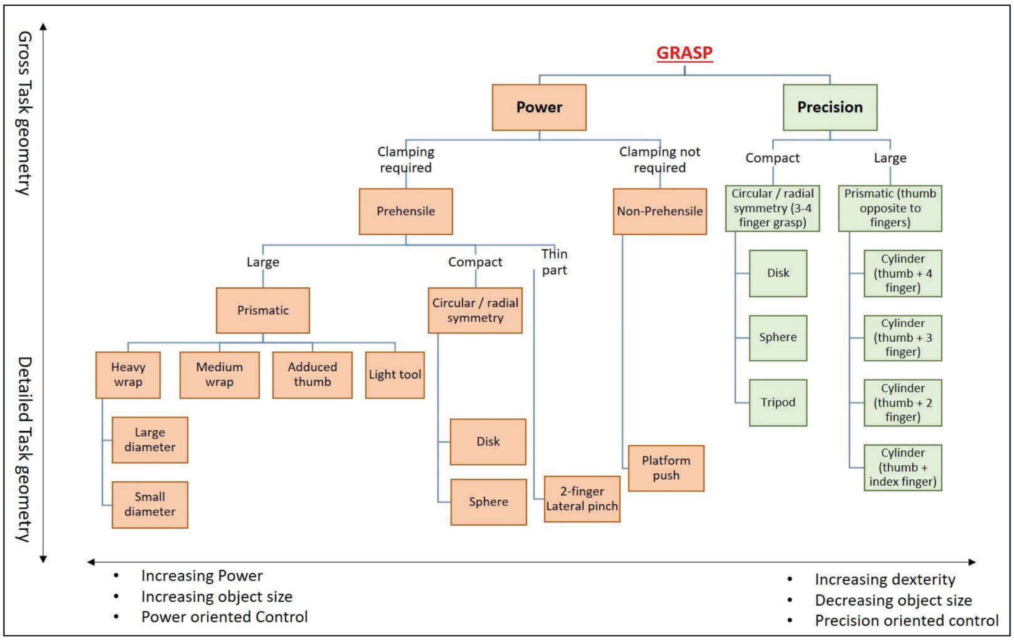

Figure 1: Classification of Grasps [7]

ii. Full actuation with 24 actuators
iii. Electro-mechanical actuation as the chosen method
iv. Use of extrinsic actuators due to space constraints
v. Tendon-driven transmission for each joint
vi. Implementation of rigid end-stops to prevent joint over-travel

1.6 Theory: Series Elastic Actuator

In Series elastic actuator, elastic member (spring) is attached in series with actuator. Actuator provides motion and output link interacts with environment. The shock of interaction is absorbed by spring.

Major advantages of SEA are as follows:

i. Can provide force feedback: The deflection δ x of the spring is measured, and force output of the actuator is estimated by k.δ x, where k is the spring constant
ii. If obstruction is encountered, it can be sensed from force feedback and Compliance due to elastic element (springs) enables gradual loading of motor before getting stall. Thus, force feedback and compliance can prevent motor stall
iii. If actuator is stuck before motion starts, motor starts at stall torque. SEA prevents motor while starting from stall condition, thus allowing to gain some momentum
iv. This provides with inherent shock tolerance and force feedback

v. Capability to store energy
vi. Less chance of damage to the environment and from the environment to system, i.e. low reflected inertia
vii. Reduces stiffness at interface and thus, well suited for human-robot interaction tasks

II. METHOD

A. Design considerations

Using data provided at source [12], target specifications finalized for this gripper are:

i. Dimensional and strength targets

Table 1: DIMENSIONAL AND STRENGTH TARGETS

S/N	Parameter	Mean Value
a)	Hand length	193 mm
b)	Hand breadth	89 mm
c)	Avg. Mass of hand	0.53 kg
d)	Grip strength	600 N
e)	Pinch hold	35 N
f)	Full hand push -static	520 N

ii. DOF and Range of motion
a. DOF = 24
b. Finger joint range of motion:
- Pitch motion for joints between metacarpal phalange and fixed base: 10 degrees
- Pitch motion for all other joints: 90 degrees
- Yaw motion for finger: 15-20 degrees
- Yaw motion for thumb: 45 degrees

iii. Grasping positions to be simulated for:
a. Primary target- Power grip:
1. Cuboid
2. Sphere
3. Shape morphing object

-Maximum mass of any object to be gripped: up to 5 kg.
-Maximum dimension of objects to be gripped: up to 100 mm.

b. Secondary targets- Precision grip: (Thumb + 2 finger) for objects like egg.

B. Estimation of Force required at actuator

Different forces acting during actuation of tendon actuated joints are shown in Fig-2. This image is based on fig-7 of [13] and modified as per our design. The segment of tendon exposed outside joint is shown in red, and this segment length varies while the joint is actuated. This image also shows the respective tendon of each joint gets routed through center of the body along green path. The path of tendon is considered to be frictionless. To identify the maximum effort all angles α,γ are considered to be 0, or else specified. From geometry h1=h2=h3 = 10 mm. Based on kinematic and dynamic model of fingers as presented by FC Chen [11], the force calculations for our design are tabulated in Table-2.

Actuator shall be of higher capacity to meet force requirements. Thus, actuator that can provide force of 250 N is selected.

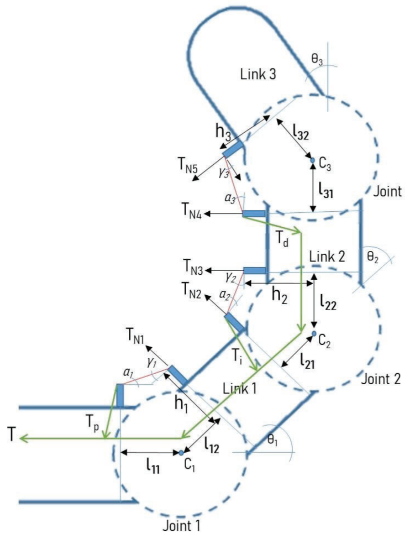

Figure 2: Forces acting on Tendon

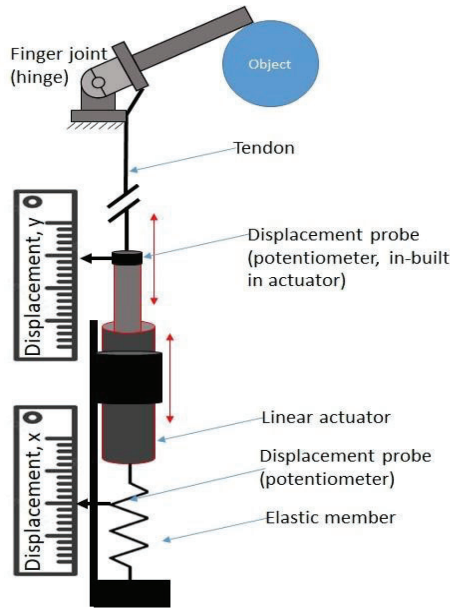

Figure 3: Implementation scheme for SEA for each joint-actuator pair

C. Implementation of Series Elastic Actuator

Refer Fig-3. Stiffness of Series elastic member > stiffness of hinge joint. With this as design consideration, following are observations.

i. As actuator moves, hinge moves. As it has less stiffness, so no deflection shall be seen in elastic member
ii. For no object / free motion, Displacement (y) denotes joint position and x = 0
iii. If object is to be handled, we move the actuator, when contact is established between object and finger, the

Table 2: FORCE ESTIMATION

	I.	II.	III.	IV.	V.	VI.	VII.
A.	Load condition	Participating fingers	Object holding stance	Phalanges in contact with object	Actuator force required at distal-intermediate joint	Actuator force required at intermediate-proximal joint	Actuator force required at proximal-metacarpal joint
B.	1- No Object	All fingers and thumb	All fingers fold to form a fist	none	10 N	10 N	10 N
C.	2-Cuboid (100x100x150 cu.mm. and 5kg)	All fingers and thumb	All four fingers holding object against thumb	Distal	$T_{N5} = 50N$, $\theta_3 = 0$, $T_d = (T_{N5} * L_{32}/h_3)/cos(\theta_3) = 100N$	$T_{N5} = 50N$, $\theta_3 = \theta_2 = 0$, $T_2 = (T_{N5} * 45) = 2250Nmm$, $T_i = T_2/h_2 = 225N$	$T_{N5} = 50N$, $\theta_3 = 90deg, \theta_2 = \theta_1 = 0deg$, $T_1 = (T_{N5} * 85) = 4250Nmm$, $T_p = T_1/h_2 = 425N$
				Intermediate	$T_{N5} = 50N$, $\theta_3 = 0$, $T_d = (T_{N5} * L_{32}/h_3)/cos(\theta_3) = 100N$	$T_{N5} = 50N$, $\theta_3 = \theta_2 = 0$, $T_2 = (T_{N5} * 45) = 2250Nmm$, $T_i = T_2/h_2 = 225N$	$T_{N5} = 50N$, $\theta_3 = 90deg, \theta_2 = \theta_1 = 0deg$, $T_1 = (T_{N5} * 85) = 4250Nmm$, $T_p = T_1/h_2 = 425N$
				Proximal	$T_{N5} = 50N$, $\theta_3 = 0$, $T_d = (T_{N5} * L_{32}/h_3)/cos(\theta_3) = 100N$	$T_{N5} = 50N$, $\theta_3 = \theta_2 = 0$, $T_2 = (T_{N5} * 45) = 2250Nmm$, $T_i = T_2/h_2 = 225N$	$T_{N5} = 50N$, $\theta_3 = 90deg, \theta_2 = \theta_1 = 0deg$, $T_1 = (T_{N5} * 85) = 4250Nmm$, $T_p = T_1/h_2 = 425N$
	Remark 1: (a) Above mentioned forces are exerted by combination of four fingers holding object against thumb.) In place of considering thumb = 4*fingers, we considered thumb to sustain actuation forces of all fingers while it is forced to physical/end limit. (c) So the maximum force on any finger joint = $T_p/4 = 106.25N$						
	Remark 2: (a) The maximum force on active finger joint = $T_p/2 = 212.5N$ (for two finger + thumb configuration)						
	Remark 3: (a) The maximum force on active finger joint = $T_p/3 = 159.75N$ (for three finger + thumb configuration)						

hinge deformation shall stop (due to object stiffness) and on further motion of actuator, deformation shall be seen in elastic member of SEA

iv. Displacement (x), denotes equivalent contact force
v. Displacement (y-x), denotes joint position

Advantage of having elastic member attached to fixed end: i. Controls backlash of tendon or actuator (if any) ii. Easy estimation of holding force exerted by SEA iii. Offset sensor for position feedback and contact force estimation.

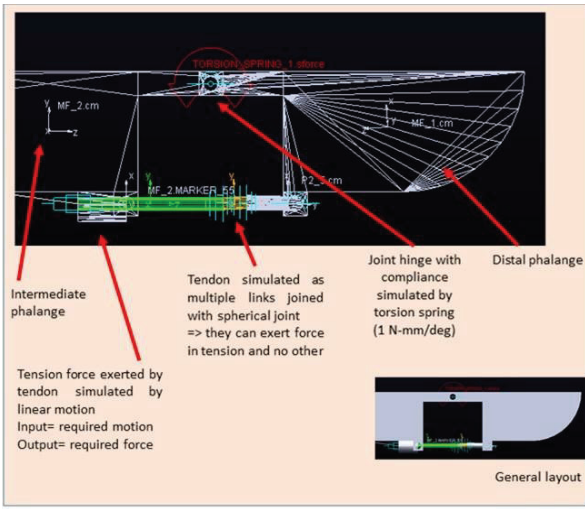

Figure 4: Compliant Joint definition for simulation of tendon

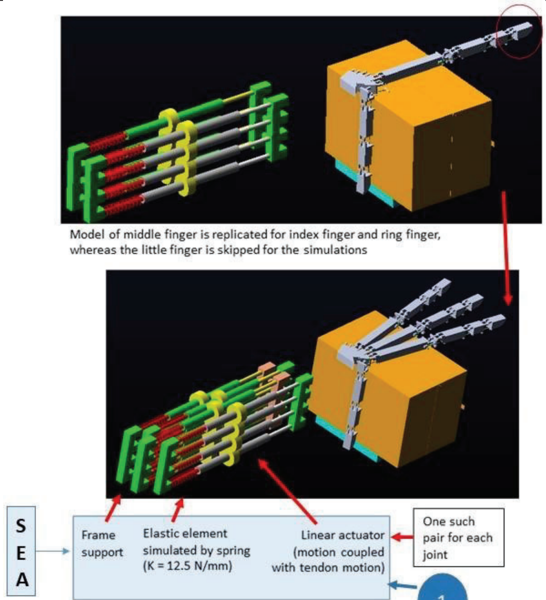

Figure 5: Model of gripper for rigid body dynamic simulations

D. Model for Rigid Body Dynamic Simulations

The proposed gripper model was developed in MSC ADAMS™ and employed for the following purposes:

i. Simulation and motion sequencing of all joints to evaluate both power and precision grip.
ii. Modelling of flexible elements, including tendons, compliant joints, and Series Elastic Actuators (SEAs).

The joint model, as defined in Fig 4 and 5, was implemented at each finger joint. A similar finger model was then extended to all fingers, with minor modifications tailored to the anatomical characteristics of each finger. Compliance at the joints was represented using a torsional spring element with stiffness of 0*1 N·mm/deg*.

Although the gripper design incorporates four fingers to mimic the human hand, the little finger contributes minimally to load-bearing and precision grasping. To simplify motion planning and reduce computational complexity, the little finger was excluded from this simulation study. The elastic element of the SEA was modeled using an extension spring with stiffness of 12.5 N/mm. Simulation results confirmed that omitting the little finger had negligible effect on the grasping operations considered in this work.

III. SIMULATION AND VALDATION OF RESULTS

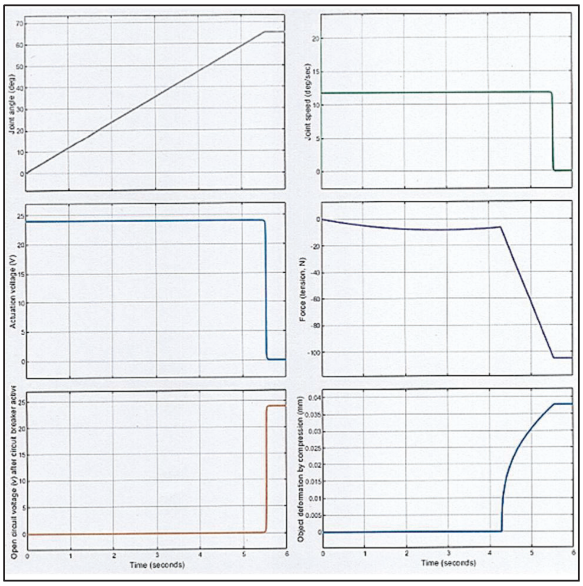

Figure 4: Simulation to verify SEA implementation scheme

A. *Verificaion of SEA implementation scheme*

The plots in fig 4, present the simulation results of a robotic gripper joint executing a grasp. This simulation was performed in Simscape, part of MATLAB R2024b [14]. The joint angle profile (top-left) shows a smooth increase up to ~65 degrees, corresponding to finger closing motion, while the joint speed (top-right) increases initially and then as the joint stabilizes at the final position, it drops to zero. The actuation voltage (middle-left) is constant at 24 V at start. When contact is made by finger with the object, the gripping force response (middle-right) shows a sharp rise to nearly 100 N, this is measured by deformation in elastic element in series. This demonstrates successful load transfer through the joint. The open-circuit voltage (bottom-left) of the simulated feedback sensor spikes at the moment of contact, confirming object interaction. The object deformation curve (bottom-right) shows positive deformation gradually increasing to ~0.35 mm after contact. Implementation of SEA allows us to control the threshold value for object interaction considering soft or hard objects. When the threshold value is reached the actuation voltage is cutoff. And the force measured at elastic element remains stored as tension in tendon. Together, these simulation results confirm that the proposed gripper design can achieve controlled motion, force regulation, and compliant object handling through Series Elastic Actuators and tendon-based actuation.

B. *Verification by Simulation*

The force determination for object handling is performed for cuboid shaped object (weight= 5 kg). To prove versatility, the model is simulated for handling following shapes and are shown below through sequence of images:

i. Cuboid with dimensions, 100mm x 100mm x 150mm and mass=5 kg: Refer Fig 7.

The gripper is in open condition and object (in yellow) is resting over stationary support (in blue). Once object is gripped, the support starts moving down gradually. The simulation shows that grip is good as the object is held firmly without slip and it loses contact with the support. The same sequence of gripping is simulated for the following objects too.

ii. Sphere with dimensions, diameter=100mm and mass=5 kg: Refer Fig 8.
iii. Egg: Refer Fig 9.
iv. Flexible body, that changes shape with time: Refer Figure10.

In this simulation the object is cuboid shaped made in two parts connected by a prismatic joint and an actuator. Initially object acts as rigid part until the gripper, grips it firmly. After grip is achieved, the actuators are further actuated to pre-load the compliant member of SEA. The grip force can be measured by deformation of elastic member. Then the base support moves under gravity and contact with object is lost confirming the grip without slip.

At this moment, the object starts to deform by suitable motion of actuator for shrinking in width. The gripper is able to maintain grip by utilizing the pre-load provided at SEA. The simulation can be visualized as a use case where gripper has to maintain gripping force even in case of power failures.

C. *Simulation results for handling Cuboid*

Refer Fig 11 and 12. Force is measured at spring element in contact with object for FINGERS (3 fingers together), Force exerted on object by

- three Proximal joints (= 508*10/P) is 69.6 N,
- three Intermediate joints (= 412*10/I) is 68.6 N
- three Distal joints (= 136*10/D) is 68 N

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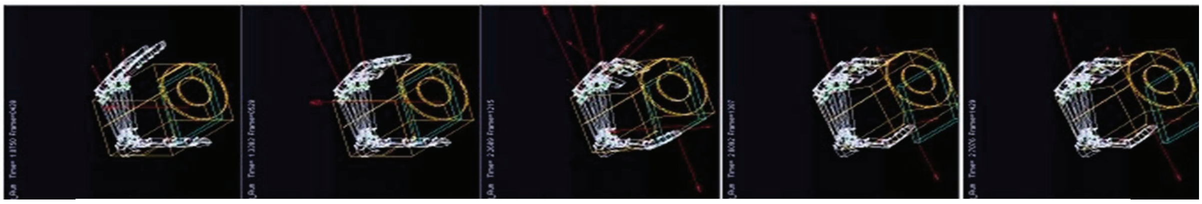

Figure 5: Sequence of action for handling of cuboid object

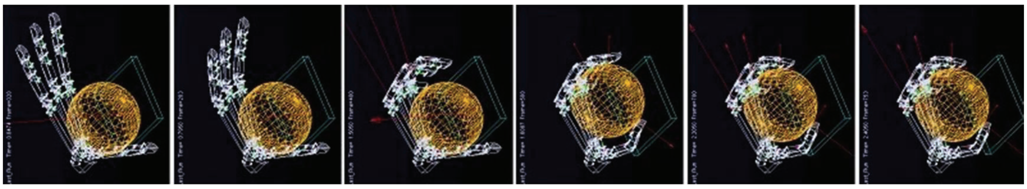

Figure 6: Sequence of action for handling of sphere

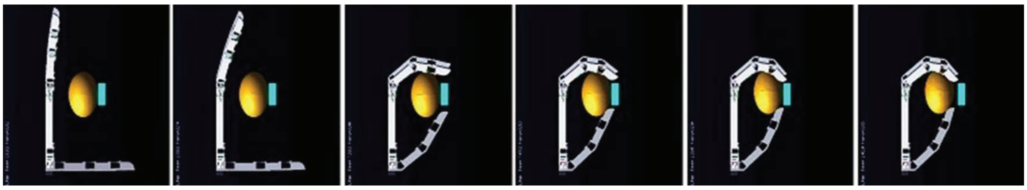

Figure 7: Sequence of action for handling of Egg

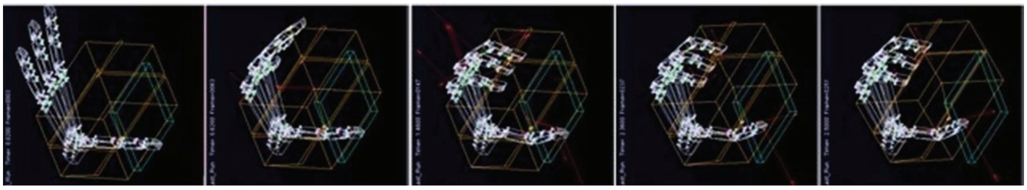

Figure 8: Sequence of action for handling of shape morphing object

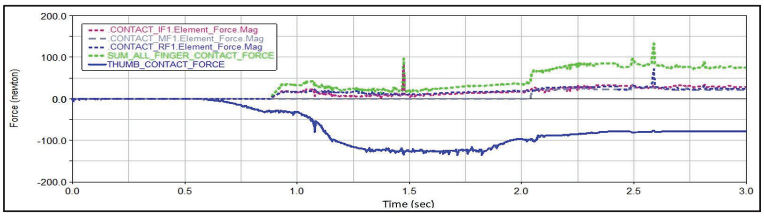

Figure 9: Forces exerted by fingers is balanced against force by thumb

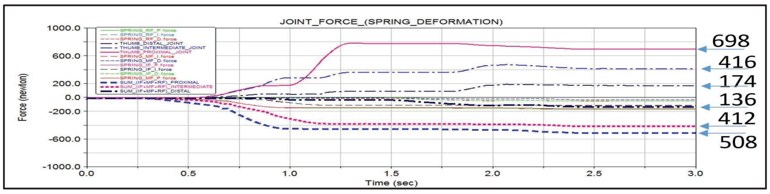

Figure 10:Forces acting coupled for each finger and thumb

For Thumb, balancing force experienced by
Proximal joint (= $698 * 10/P_T$) is $69.8N$
Intermediate joint (= $416 * 10/I_T$) is $69.3N$
Distal joint (= $174 * 10/D_T$) is $69.6N$
It is observed that for gripping object firmly, force exerted by three fingers is proportionally balanced by thumb. Considering force on individual joint of fingers, the maximum pull force is required at proximal location =508/3 =169.33 N. The additional force is above the estimated force (mentioned in table:2). This extra grip force forms the preload by deforming spring element of SEA.

D. Inferences from simulation results

i. The conceptual scheme for SEA was successfully simulated for stable gripping of objects, validating the feasibility of the proposed approach.
ii. The scheme enabled to reliably perform power and precision grasps.
iii. Independent actuation of each joint is essential for achieving dexterity.
iv. Compliance (SEA modeling) ensures safe interaction and adaptability to irregular shapes.
v. The final actuation scheme requires a clear layout for 24 actuators (to mimic human hand) along with provision for wrist DoFs and electronics.
vi. Simulation validates the feasibility of the mechanical arrangement before moving to prototyping.

E. Final anthropomorphic gripper, realized

The final design is realized by selective laser sintering of hand as single component. All the actuators (SEAs) are assembled in the fore-arm section as shown in Fig-13.

F. Final comparison with dimensional targets for achieving spatial arrangement of human hand

The dimensional and kinematic targets were set at para 2.1. The comparison table with achieved values against target values is given at Table 3: Comparison table showing achieved values vs target values.

I. Testing and Evaluation

All 24 actuators and 48 sensors were successfully integrated according to the proposed SEA implementation scheme. The system was experimentally evaluated by actuating individual joints and recording joint positions and contact forces through spring deformations, thereby validating the position–force sensing approach. Soft grasping capability using SEAs was demonstrated.

The gripper's performance was further assessed through 50 repeated gripping and releasing cycles of a cuboid object. Results showed consistent operation with stable performance, confirming both the repeatability and durability of the concept. Reliability tested under power-loss conditions as objects remain held because of preload. These outcomes validate the SEA-based implementation for precise position and force feedback across all joints, reinforcing its suitability for anthropomorphic gripper applications. The integrated gripper is shown holding cuboid and spherical shape objects in fig. 14.

Limitations: The steel cable that is routed through multiple joints experiences bends and friction while sliding along the internal pathways and is causing reduced return motion

This gripper demonstrates feasibility of using SEAs in a high-DoF anthropomorphic gripper, bridging the gap between rigid robotic hands and soft robotics.

Table 3: COMPARISON TABLE SHOWING ACHIEVED VALUES VS TARGET VALUES

I.	Dimensional requirements of Anthropomorphic hand			
Sr.No.	Requirements	Targets	Achieved	deviation (in percentage)
a.	Hand length (maximum)	200 mm	250 mm	25 percent high
b.	Hand breadth (maximum)	100 mm	100 mm	0 percent high
c.	Hand mass (maximum) without actuators	0.6 kg	0.2 kg	66 percent less
d.	Position of CG from base	75 mm	100 mm	

II.	Degrees of Freedom and Range of Motion			
Sr.No.	Requirements	Targets	Achieved	deviation (in percentage)
a.	DoF	24 (for full hand)	24	0
b.	Finger Joint	Pitch motion for joints between metacarpal phalange and fixed base: 10deg	10 deg in pitch for said joints, achieved through physical joint limits.	0 0 0
c.	Finger Joint	90 deg for each joint in pitch	90 deg in pitch	0 0
d.	Finger Joint	15-20 deg in yaw for finger and 75 deg yaw for thumb	30 deg in yaw for fingers and 75 degree for thumb, achieved through physical joint limits.	0 0 0

III.	Design Verification			
Sr.No.	Object Shape	Simulation for handling	Experimental Verification	Remarks
a.	Cuboid	Simulation results show adequate gripping action	Refer Figure-15a	Handling of a cuboid (100mmx100mmx200mm)
b.	Sphere		Refer Figure-15b	Handling of a sphere (100mm diameter)
c.	Egg	show adequate		was not part of this study, actual for remaining items will be future scope.
d.	Flexible body			

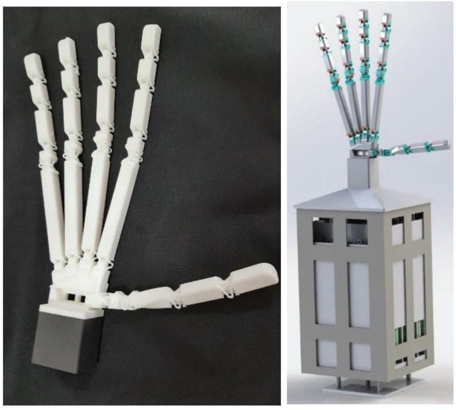

Figure 123: Final Design, realized through SLS

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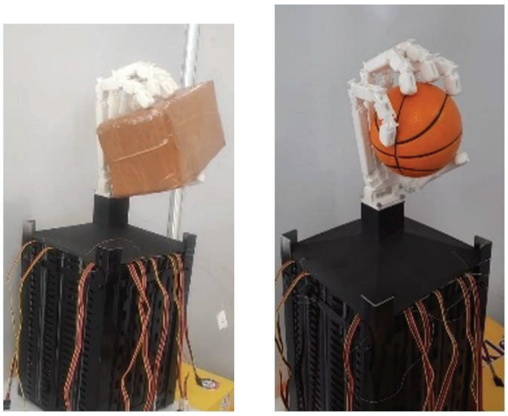

Figure 114: (a) Gripping a cuboid shaped object (b) Gripping a spherical shaped object

II. OUTCOME AND FUTURE SCOPE

The proposed anthropomorphic gripper achieves its design objectives while offering promising potential for further research and application. The spatial arrangement of the prototype is approximately 1.25 times longer than the human hand while maintaining full hand functionality, and with only one-third of the human hand's weight**.**

Key outcomes of this project include:

a) Accurate replication of human hand joint positions and motion ranges.

b) Realization of a 24-DoF, fully actuated gripper, meeting all targeted performance specifications.

c) A novel SEA-based actuation and sensing scheme**,** enabling actuators and sensors to be positioned in the forearm rather than at the joints. This configuration requires only two position sensors per joint to provide both position and force feedback.

d) Successful validation of the SEA scheme through both dynamic simulations and experimental testing**.**

Building on these achievements, the gripper opens multiple avenues for future research, including:

- Integration of sensor embedded skins for enhanced tactile perception and manipulation feedback.
- Development of customized compact actuators to further optimize size and space utilization.
- Improvements in gripping strength, adaptability, and dexterity**,** enabling broader applicability in humanoid robotics, and collaborative robot systems.

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