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Enhancing Load-Carrying Capacity of a Tendon-Driven Soft Robotic Gripper Through Pneumatic Stiffness Modulation

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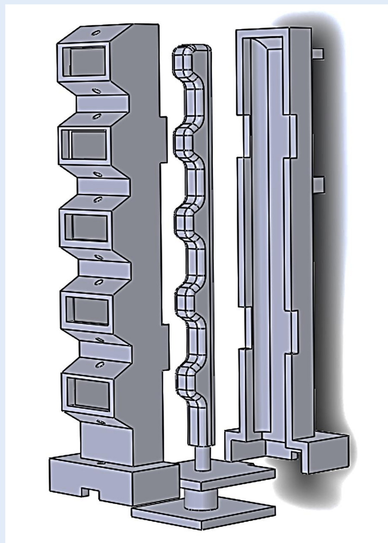
Introduction

- Soft grippers ensure safe, adaptive grasping, but lack precision and load-bearing strength without active stiffness control.
- **Our goal:** Design a tendon-driven, pneumatically stiffened three-finger gripper and analyze the relation between its stiffness, torque demands, and load capacity.
- **Motivation:** Pneumatic modulation offers a fast, low-power, and reversible way to balance compliance with strength across diverse robotic tasks.

Finger Design

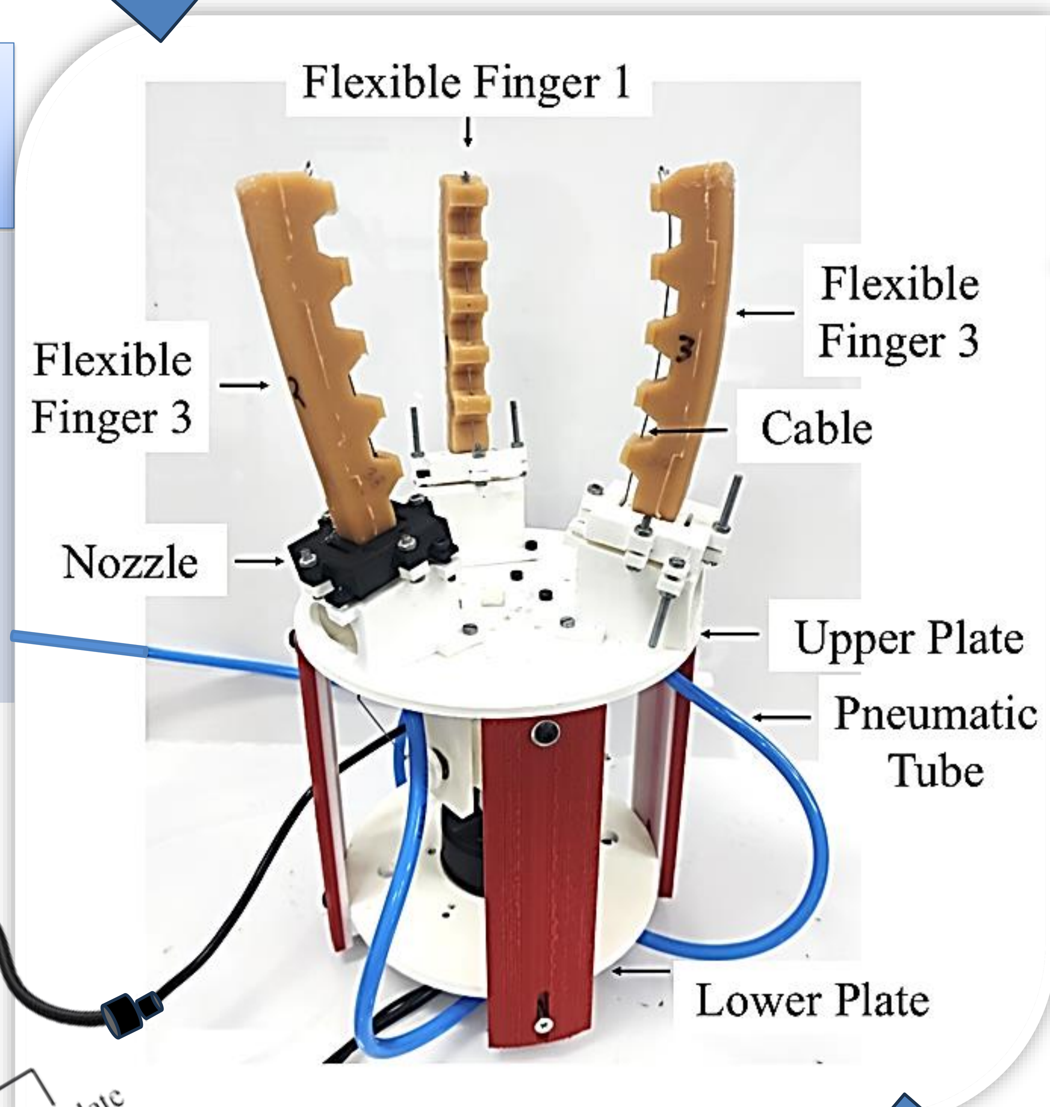
- Molded from **VytaFlex-40**
- **Single-chamber pneumatic bladder** embedded inside
- 3-part Mold ensures precise cavity formation
- Tendon-guiding channel integrated for cable-driven actuation

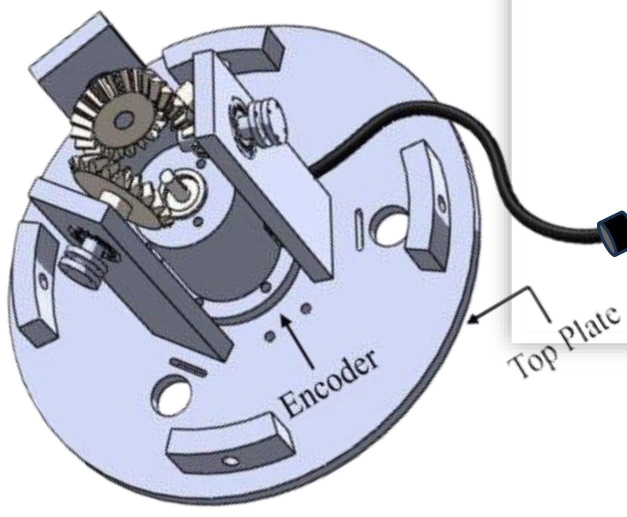


Mold Design

Tendon-driven actuation

- Single **BLDC motor (T-Motor P60 KV170)**
- **Bevel gear** drives 3 synchronized pulleys
- **ODrive v3.6** in position control



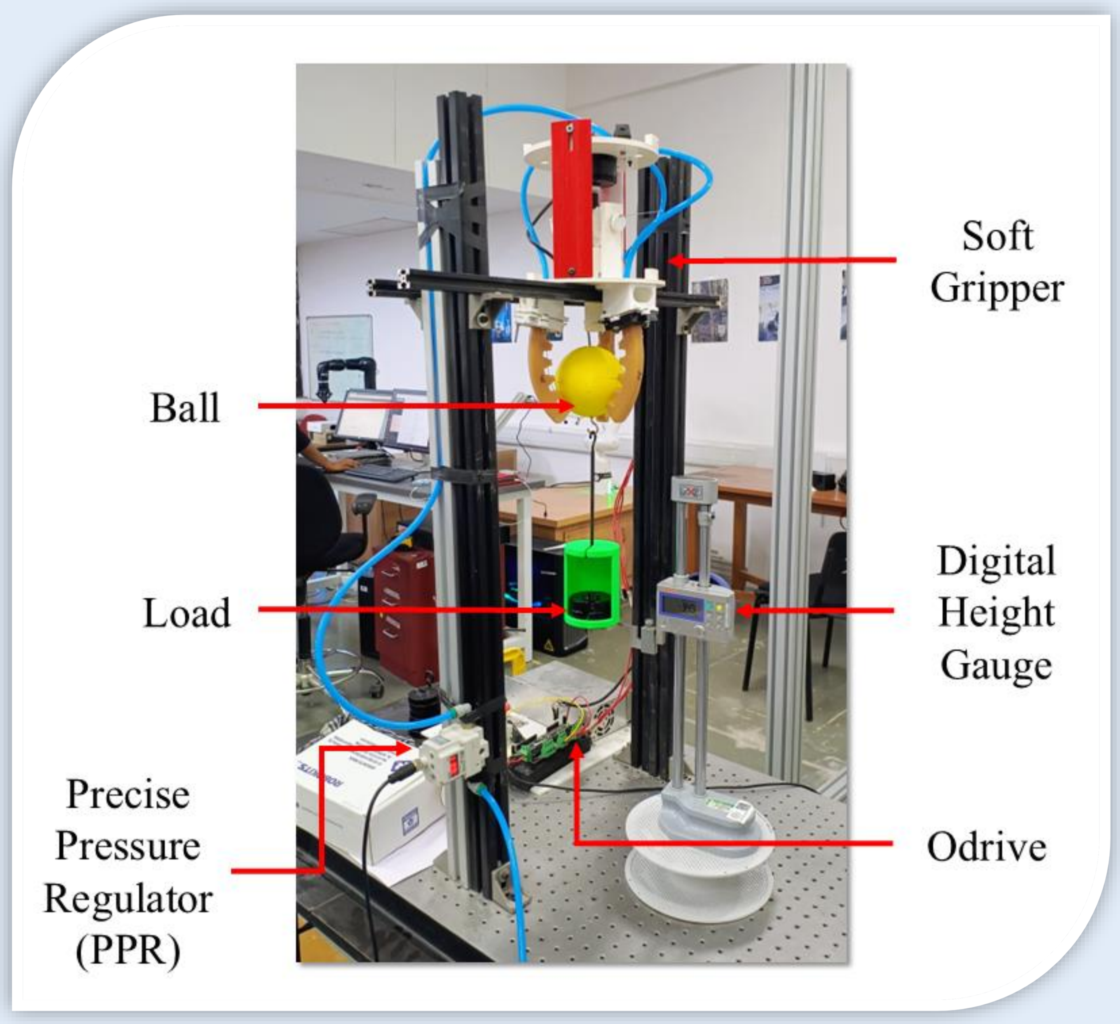


SMC PPR

Variable Pneumatic Stiffness

- Air chamber inside each finger
- Pressure range: 0-1.2 kgf/cm^2
- Control via SMC PPR

Experiments



Experimental Setup

Procedure

Set Internal Pressure
- (0, 0.4, 0.8, 1.2 kgf/cm^2)
- using SMC PPR

Actuate Gripper Fingers
- After 50 sec rotate motor to 0.3 rev (approx. 108°)

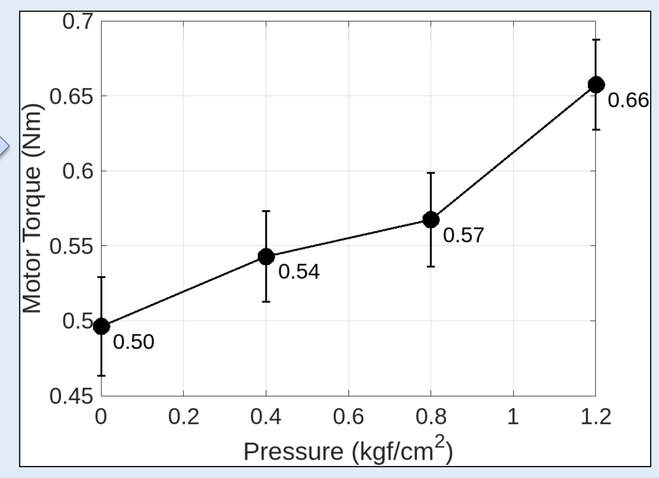
Measure Motor Torque Output
- Recorded via ODrive's internal sensing

Repeat for All Pressure Levels
- Ensure consistent position & procedure

Repeat Each Test 5 Times
- Calculate mean & standard deviation

Plot Torque vs. Pressure
- Analyze how internal pressure change affects actuation demand

Results



Experiment 1: Effect of Internal Pressure on Actuation Effort

Set Internal Pressure
- 0, 0.4, 0.8, 1.2 kgf/cm^2
- Using SMC PPR

Actuate Gripper Around Ball
- Rotate motor to 0.5 revolutions
- static fingertip grasp achieved

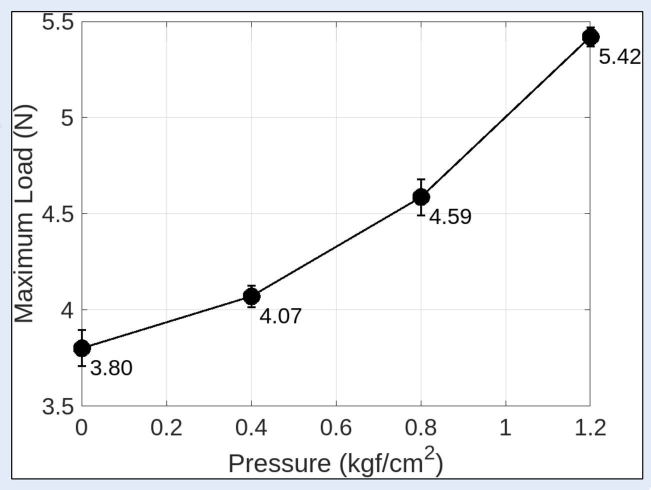
Hang External Load (Coarse Increments)
- Add 50 g weight every 50 sec
- Continue until slippage is observed

Repeat Coarse Loading
- Repeat the experiment by adding coarse loads (50 g)
- till time = (t – 50 sec)

Hang External Load (Fine Increments)
- Add 10 g weight every 50 sec
- Stop when ball slips out of the grasp
- Record maximum load held (N) for current pressure level

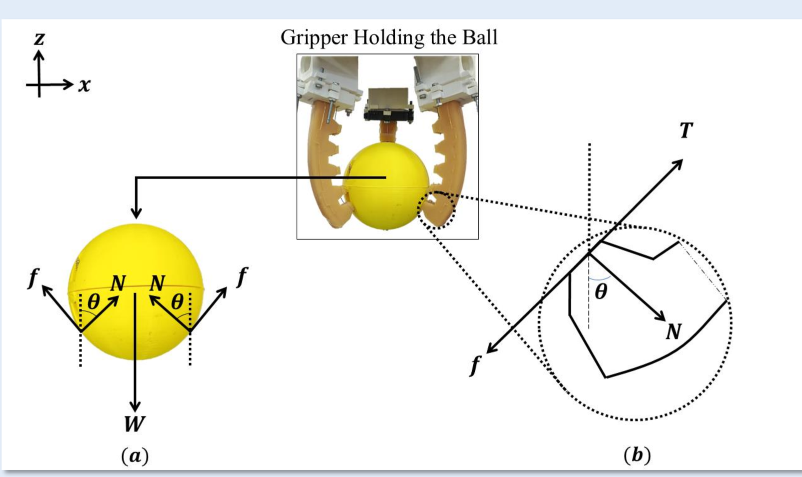
Repeat Each test 5 times
- Calculate mean & standard deviation

Plot Max Load vs. Pressure
- Compare grasp strength across pressures



Experiment 2: Impact of Pressure Modulation on Load-Carrying Capacity

Equations



Free body Diagrams of (a) the ball, (b) the Fingertip

$$T \propto N \propto W$$

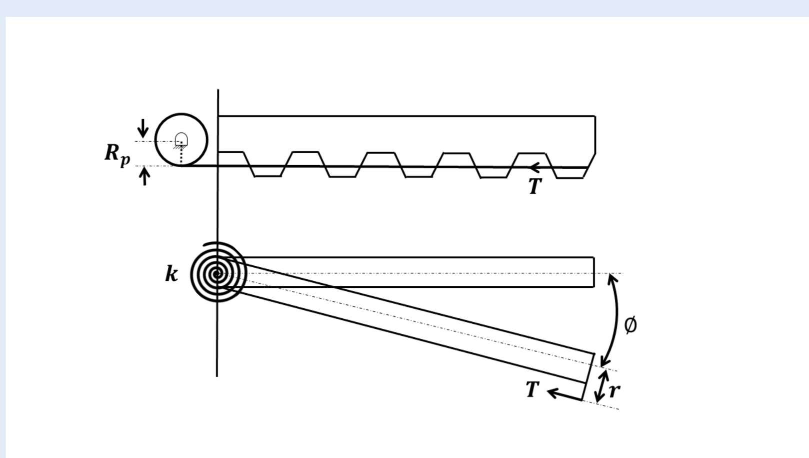


Figure: Pseudo-Rigid body model of the finger

$$K \propto T \propto T_m$$

Final relation

$$K \propto T \propto N \propto W$$

Key findings

- Motor torque increases with internal pressure, a **150%** improvement.
- Grasping force increased up to **42%** when the fingers were pressurized.
- Four trials per pressure level give standard deviation ($\sigma < 5\%$), showing consistent performance
- Experimental torque and load data confirm the predicted chain $K \propto T \propto N \propto W$ from the pseudo-rigid-body model analysis

Future Work

- Quantify the dynamic relationship between Finger stiffness, tension, and load during real-time grasping tasks.
- Detect object Stiffness for enhanced precision in grasping and manipulation
- Detect slip accurately to autonomously adjust finger pressure and improve grip force.

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