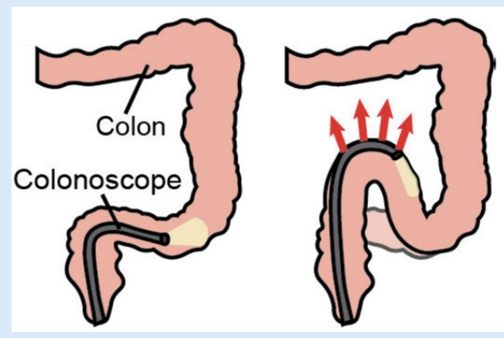
A Neural Network for Real-Time Force Monitoring in a Soft Robotic Sleeve for Safer Colonoscopies

Emma Capaldi[1,2], Viola Del Bono[2], Sheila Russo[2]

Phillips Academy Andover, 180 Main Street, Andover, MA, 01810[1], Boston University Material Robotics Lab, 730 Commonwealth Avenue, Boston, MA 02446[2]

Background

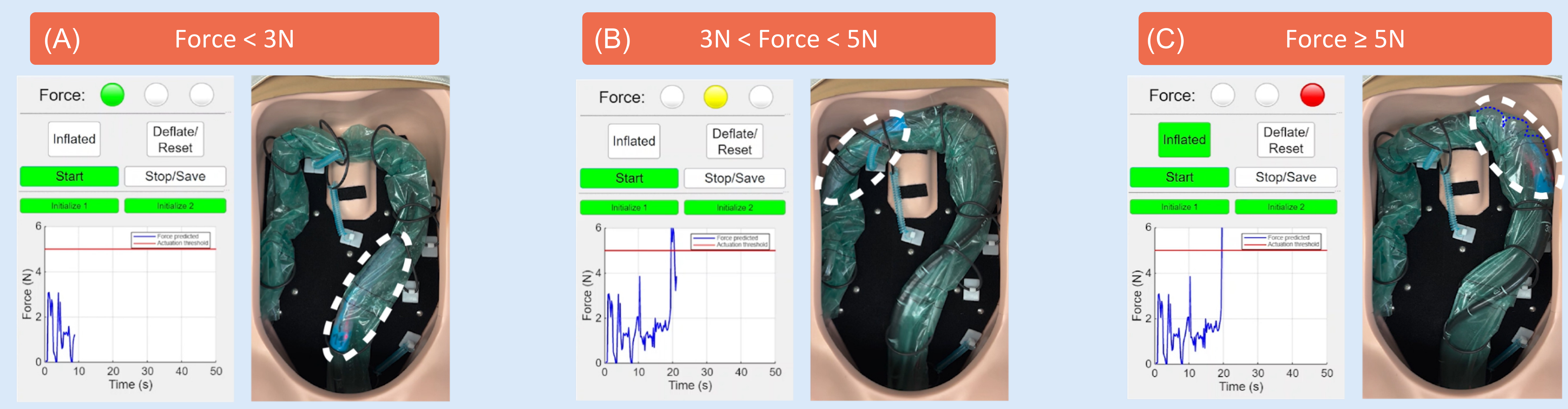
- Colonoscopies are important for early detection of colorectal cancer
- Colorectal cancer is the third most common cancer, with an estimated 153,000 new diagnoses and 52,000 deaths in the US in 2023 [1]
- However, current colonoscopy procedures are not able to monitor and minimize internal contact forces [2]
- This can lead to severe adverse events (SAEs) like tissue perforation, bleeding, and death [3], [4]
- Occurrence rates of SAEs are relatively rare (0.035-0.23%), but more than 15 million colonoscopies are performed in the US yearly [5], which could mean 5,250-34,500 SAEs per year
- **A robotic add-on could monitor contact forces between the colonoscope and the colon and automatically redistribute the force load accordingly**



Excessive force on colon from colonoscope can lead to SAEs

Testing

Testing of the sleeve was performed in-vitro on a phantom colon, ex-vivo in a bovine tissue sample, and in-vivo in a live pig.

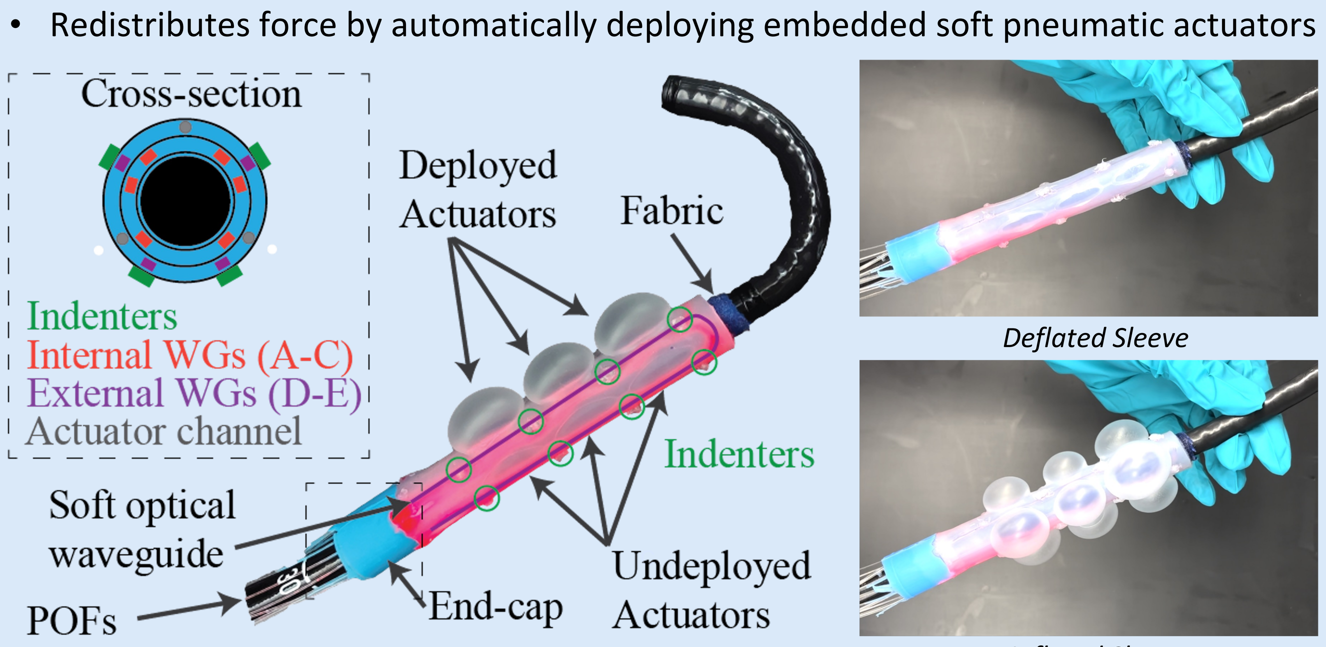


Screenshots of control graphic user interface and live video from in-vitro testing of sleeve on a phantom colon. (A) low force less than 3N (B) intermediate force between 3N and 5N (C) high force above 5N, which triggers automatic inflation of sleeve for force redistribution.

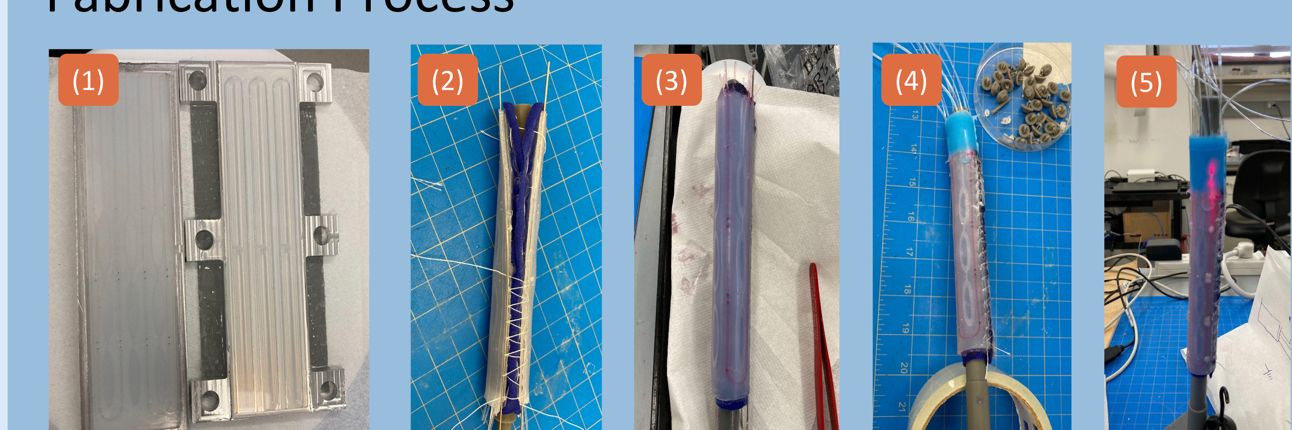
Soft Robotic Sleeve

A soft robotic sleeve that fits around existing colonoscopes was developed

- Monitors contact forces between the colon and the colonoscope using embedded soft optical waveguides
- Redistributes force by automatically deploying embedded soft pneumatic actuators



Fabrication Process



(1) silicone is cured in various molds (2) silicone components are assembled and the sleeve is wrapped (3) optical adhesive is injected to form waveguides (4) indenters for force magnification are affixed to exterior (5) optical fibers are connected to sleeve

Force Sensing

Bending during navigation or deformation due to force causes optical sensors to experience a change in intensity.

This change in intensity can be used to determine the magnitude of the contact force.

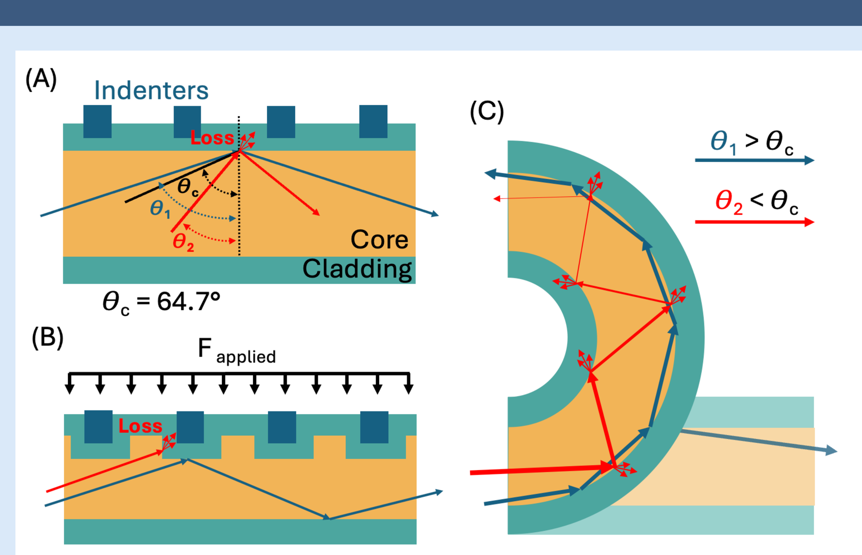
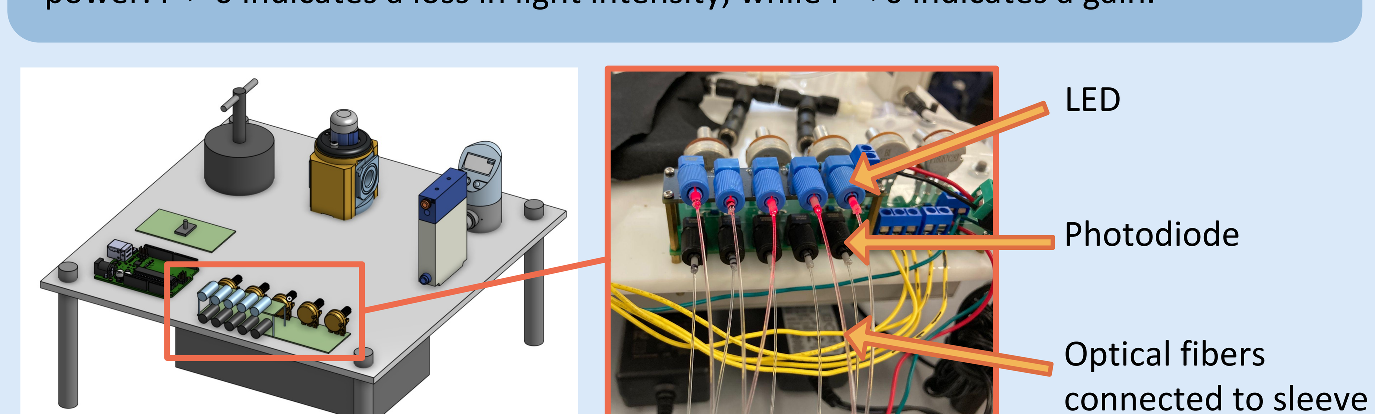


Illustration of light path in waveguide when (A) undeformed (B) deformed due to applied force (C) deformed due to bending

Change in intensity is calculated using the optical energy loss function:

$$P = 10\log_{10}(I_0/I)$$

Where I_0 is the output power of an undeformed waveguide, I is the current power through the waveguide as measured by a photodiode, and P is the change in output power. P > 0 indicates a loss in light intensity, while P < 0 indicates a gain.



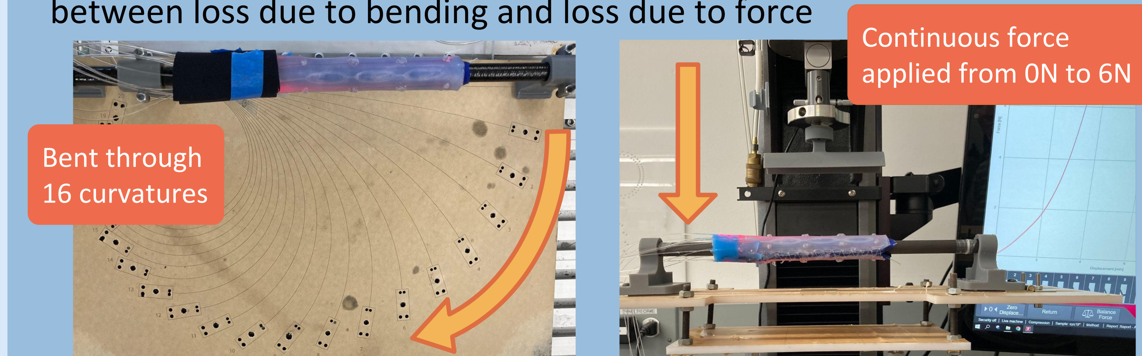
Configuration of electronics board for controlling and measuring changes in light intensity in optical waveguides

Neural Network

A feed-forward neural network was developed in MATLAB that uses calculated losses from the optical sensors to determine the contact force.

Force and Curvature Calibration Process

The network is trained on two calibration datasets so it can distinguish between loss due to bending and loss due to force

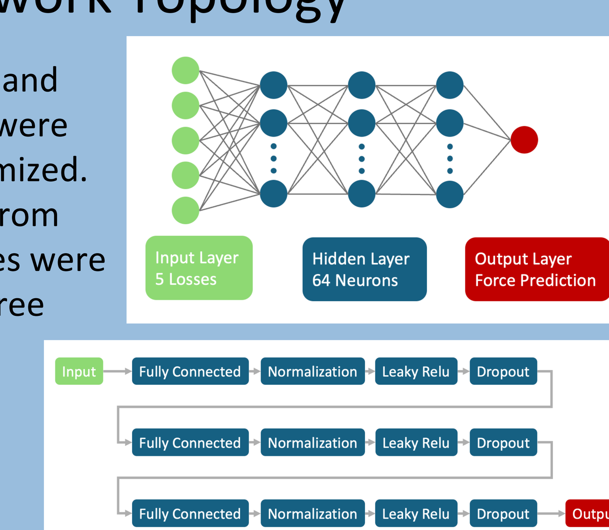


Setup for bending calibration. Optical loss measurements are taken at each curvature. 5 trials are taken in each of 6 orientations of the sleeve (0°, 60°, 120°, 180°, 240°, 300°).

Setup for force calibration. Optical loss measurements are taken continuously. 3 trials are taken in each of 4 orientations of the sleeve (60°, 120°, 240°, 300°).

Neural Network Topology

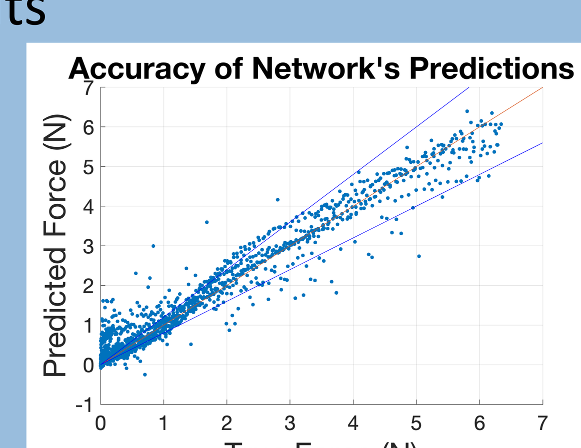
Network topology and hyperparameters were explored and optimized. Calculated losses from the five waveguides were passed through three hidden layers to predict contact forces.



Final network topology.

Initial Results

The model was initially trained on force calibration trial 1 and 2 and tested on calibration trial 3.



Measured force vs predicted force. Red line indicates perfect correlation, blue lines indicate ±20% error range.

Confusion Matrix

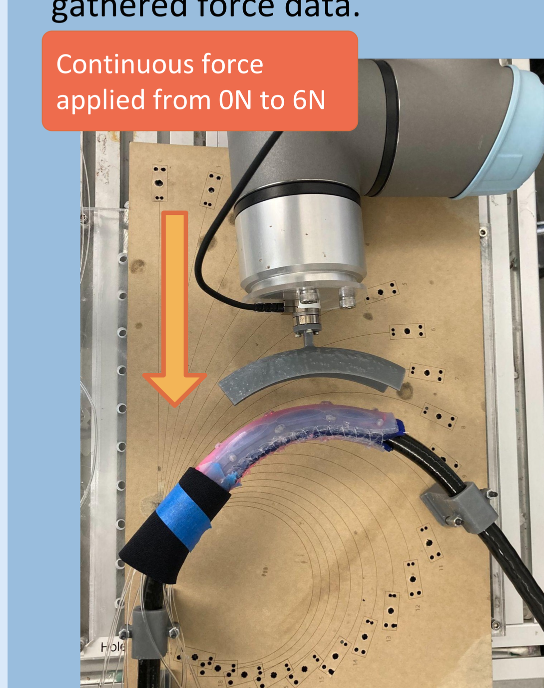
True Force (N) \ Predicted Force (N)	0-3	3-5	5+
0-3	1040	19	
3-5	17	179	5
5+	1	19	70

Roughly 98% of predictions correctly identified the force as above or below the actuator deployment threshold (5N).

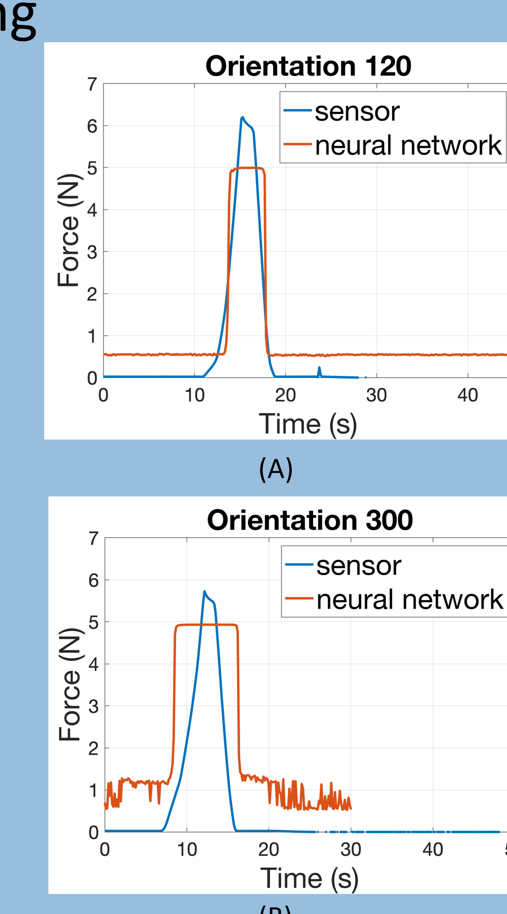
Confusion matrix of predictions, classifying forces into one of three categories used during instrument operation.

Force Validation Testing

The model was then trained on all force calibration trials and tested on independently gathered force data.



Robot arm used to apply force to sleeve bent to curvature 10 m^{-1}. This was repeated in 6 orientations (0°, 60°, 120°, 180°, 240°, 300°).



Force sensor readings and neural network predictions were compared over time. Predictions accurately capture major changes in force.

Discussion

The soft robotic sleeve has the capacity to greatly improve the safety of colonoscopies by providing force-monitoring and force-redistribution capabilities, as demonstrated in a variety of testing environments.

The neural network shows great promise as it simplifies the calibration process of the robotic sleeve, and with large datasets has the potential to monitor forces with high degrees of accuracy.

Additionally, the neural network can be used to perform real-time force monitoring when incorporated into a control graphic user interface.

Control GUI incorporates neural network force predictions.

Future Work

- Automate calibration process to obtain a larger training dataset for the neural network
- Test functionality of the neural network in-vitro to demonstrate force-monitoring capabilities during navigation

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