Miniature Robotic Tubes with Rotational Tip-Joints as a Medical Delivery Platform

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Introduction

This study examines the prospect of thin, needle-sized *robotic* tubes with **M-DOF hinge-joints** as a medical delivery platform.

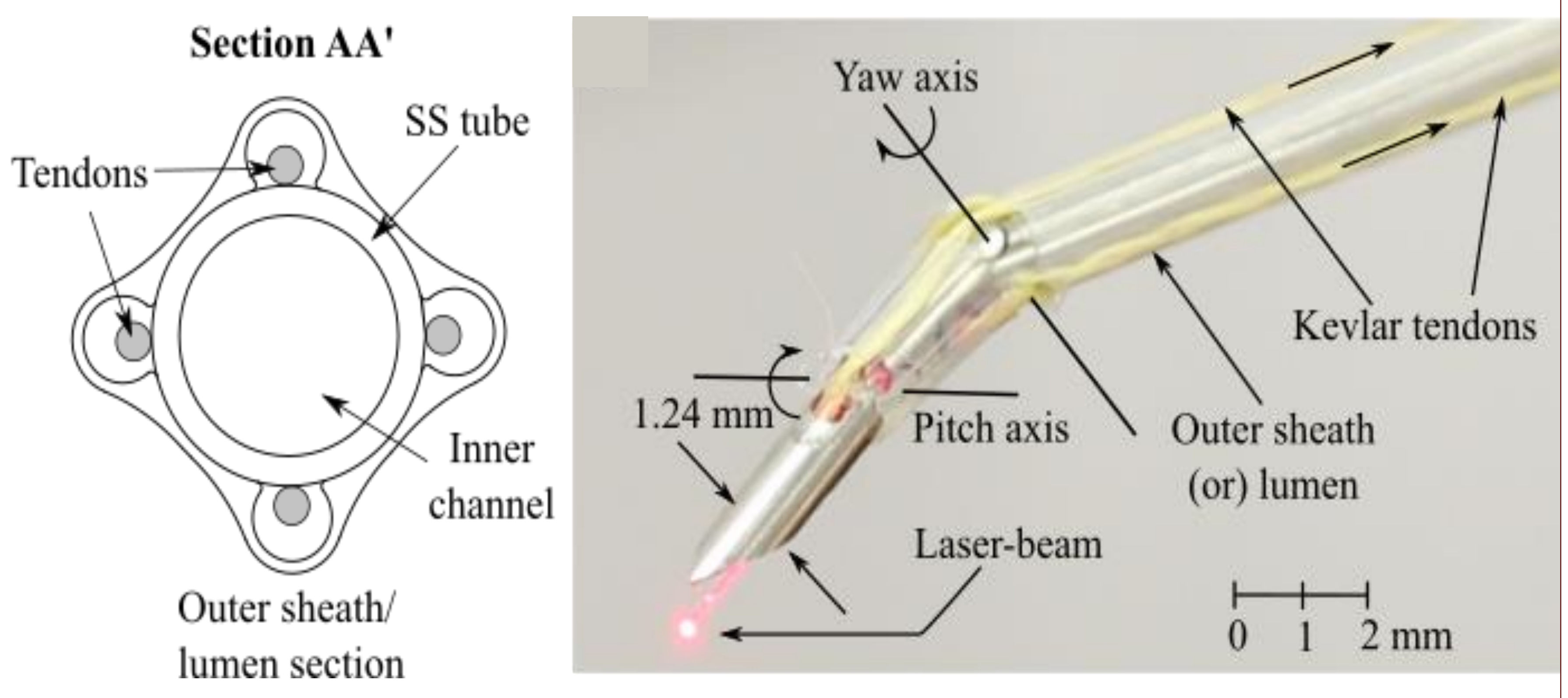
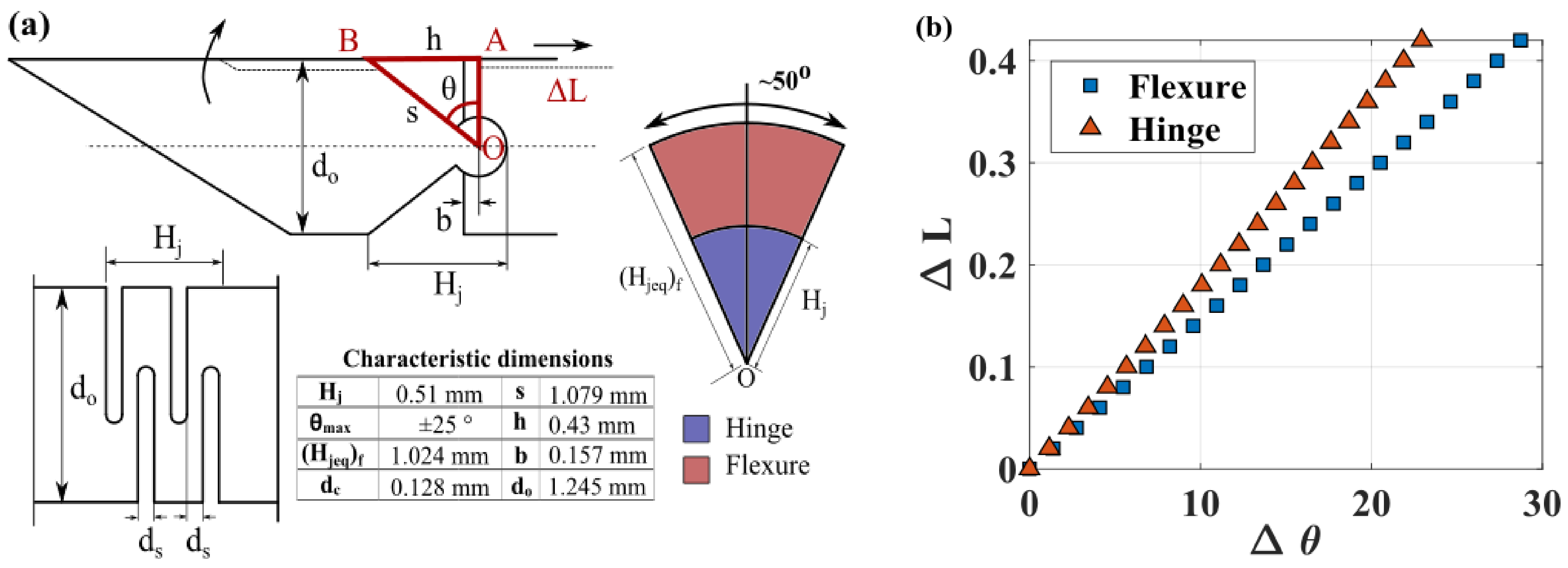


Fig. 1: Schematic of proposed 2-DOF instrument laser-machined on an 18 Ga (**BWG**) SS-316 tube. (left) Instrument cross-section with outer lumen.

- **Rationale:** Current design choices are limited by workspace constraints, control challenges, manufacturing, and function.
- **Hypothesis:** Thin, needle-sized devices with laser-machined M-DOF hinge-joints may offset some of these issues in practice.
- **Approach:** We demonstrate the superiority of the hinge by **(i)** contrasting its kinematics with the flexure, **(ii)** experimentally investigating the axial and lateral strength, and **(ii)** illustrating its kinematic controllability through simple path-tracing experiments.

Kinematic Comparison

The hinge relies on fewer simplifying assumptions related to its behavior, when compared to its flexure counterpart, and hence proffers better kinematic controllability, and precision.



Characteristic dimensions

H_j	0.51 mm	**s**	1.079 mm
θ_{max}	±25 °	**h**	0.43 mm
$(H_{jeq})_f$	1.024 mm	**b**	0.157 mm
d_c	0.128 mm	**d_o**	1.245 mm

Fig. 2: **(a)** Schematic of hinge and flexure with constraint **(i)** and a pie-diagram of swept area under constraint **(ii)**. **(b)** Plot comparing deflection of flexure and hinge-type joints against tendon extension.

- Metrics for comparison: **(i)** tip deflection, and **(ii)** swept volume.
- Constraints: equal **(i)** axial length, and **(ii)** maximum deflection.
- The hinge permits compact articulation i.e. tighter curvatures within limited workspaces, and reduces distal tool foot-print.

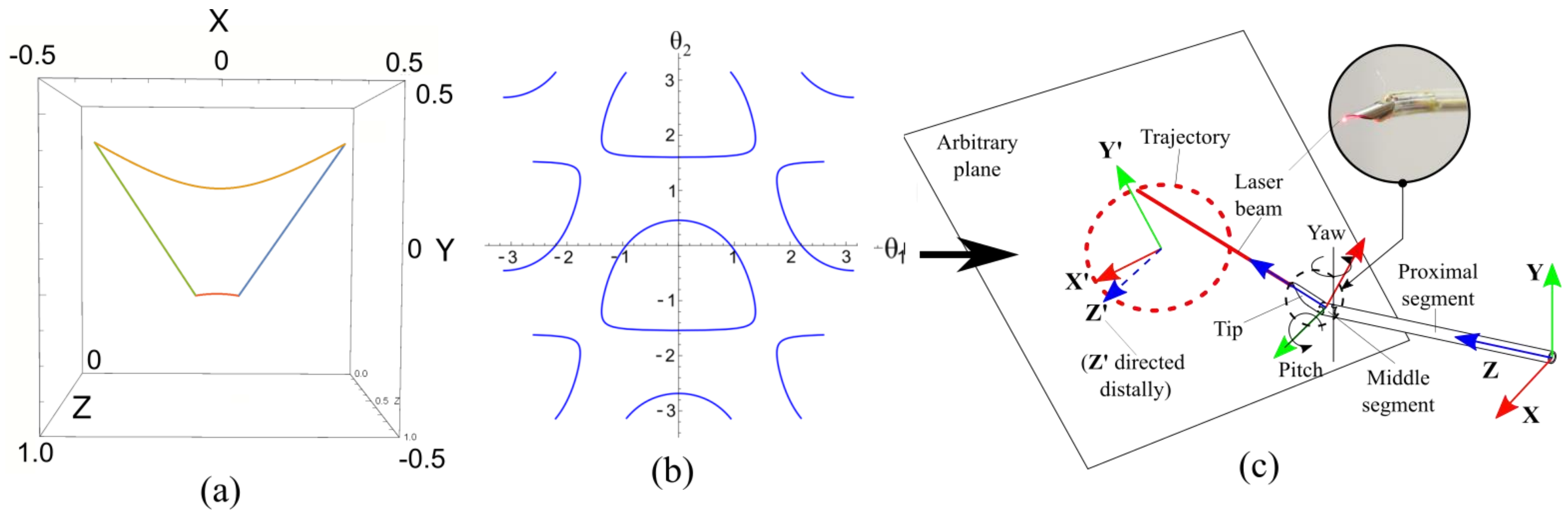


Fig. 3: **(a)** Boundaries of the projected tip on an inclined plane when the hinges are at their actuation limit for a 2-DOF hinge-jointed robotic arm, **(b)** possible solutions to generate the desired elliptical/ circular trajectory on an arbitrary reference plane, and **(c)** schematic representation of projection tracing on an inclined surface using the articulate instrument.

Joint Strength

Physical connections are absent between the socket and pin, hence, there are concerns about joint strength. We dispel this perceived demerit by studying the load thresholds on the joint.

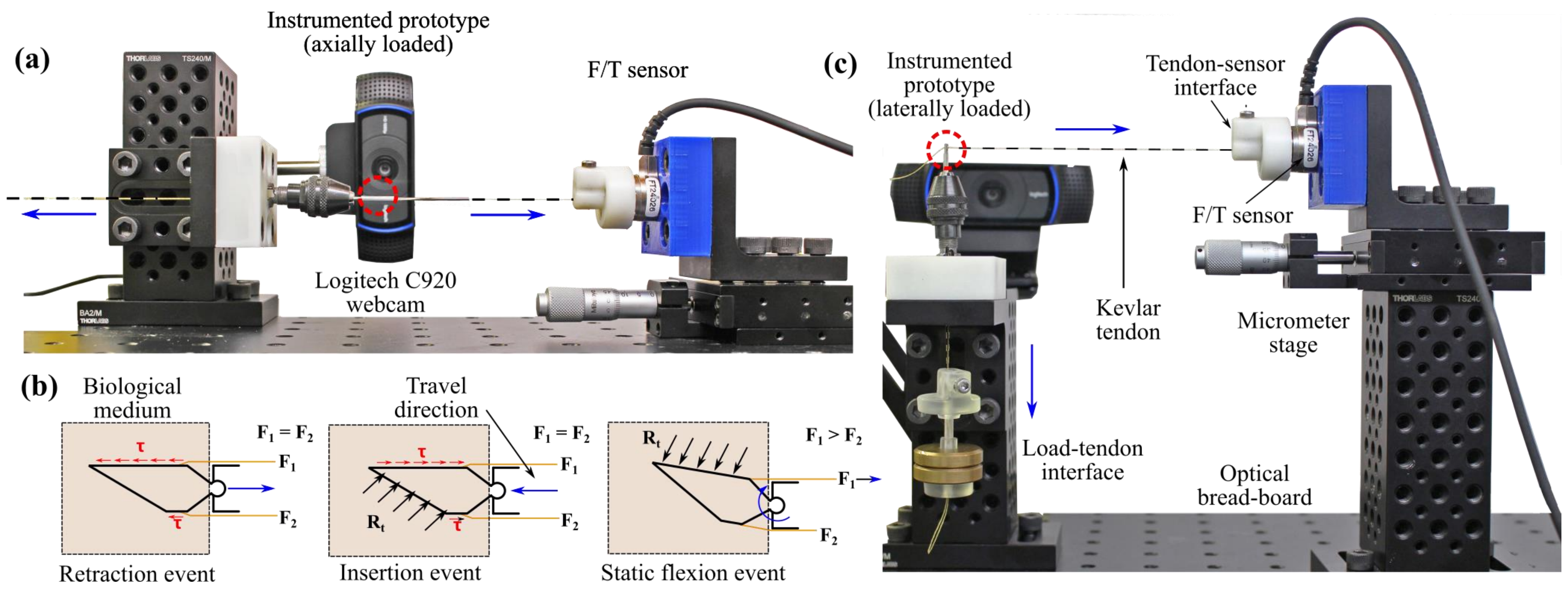


Fig. 4: Experimental setup for strength experiments on hinge-jointed specimen: **(a)** axial, **(b)** common loading conditions, and **(c)** lateral.

1. Two measures for strength: **(i)** axial, and **(ii)** lateral strength
2. Specimen: **(i)** machined tube**,** and **(ii)** instrumented prototype.
3. Material: SS-316 (thick, thin-walled), and super-elastic Nitinol.
4. Hinge configurations: *40*, *50*, and *60 %*

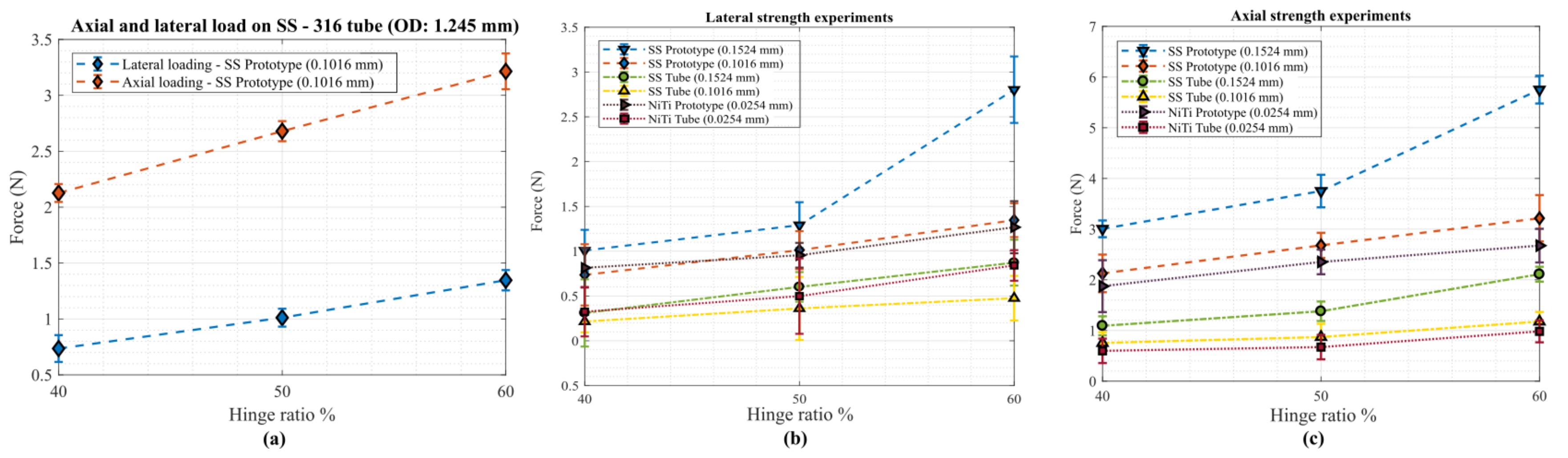
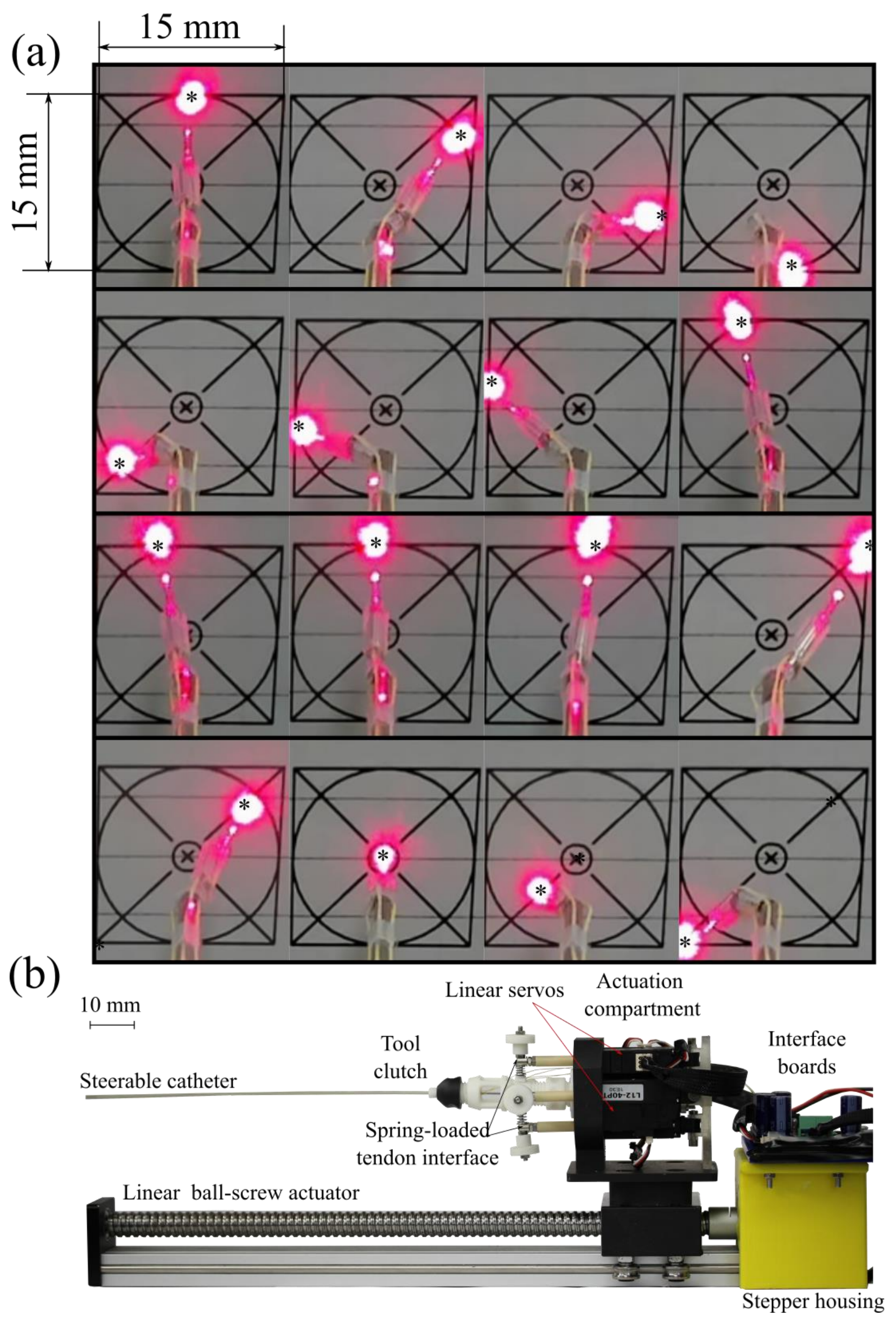


Fig. 5: Plots depict load at failure for tube and prototype specimen under axial and lateral loading conditions. **(a)** Super-imposed plots for axial and lateral load on SS-316 prototype (0.1016 mm), **(b)** lateral strength data, and **(c)** axial strength data.

The hinge when reinforced by the tendons and lumen, with and overlap ratio of *60%* is sufficiently robust for medical device applications such as the one proposed in this study.

Path Tracing Demonstration



- Simple projection tracing experiment using a custom instrument manipulator.
- Utilizes kinematic model introduced in preceding sections, enables precise tip-positioning.
- RMS error was approximately: *0.368 mm*, for the paths so depicted.

Fig. 6: Projection tracing using an optical fiber: **(a)** montage of laser-beam tracing a circle on an arbitrary plane offset from the instrument's tip, and **(b)** the driving system used for kinematic validation and path tracing.

Conclusion

The rotational hinge joint offers an intuitively simple model under fewer simplifying assumptions, it **(i)** enables compact articulation, and smaller tool sizes, **(ii)** is sufficiently robust for in-vivo use, and **(iii)** is demonstrably capable of precise tip-positioning.

ICRA 2019 05/21/2019 15:15 – 16:30 #2839