A Bio-Inspired Tendon-Driven Continuum Robot for Treatment of Twin-to-Twin Transfusion Syndrome

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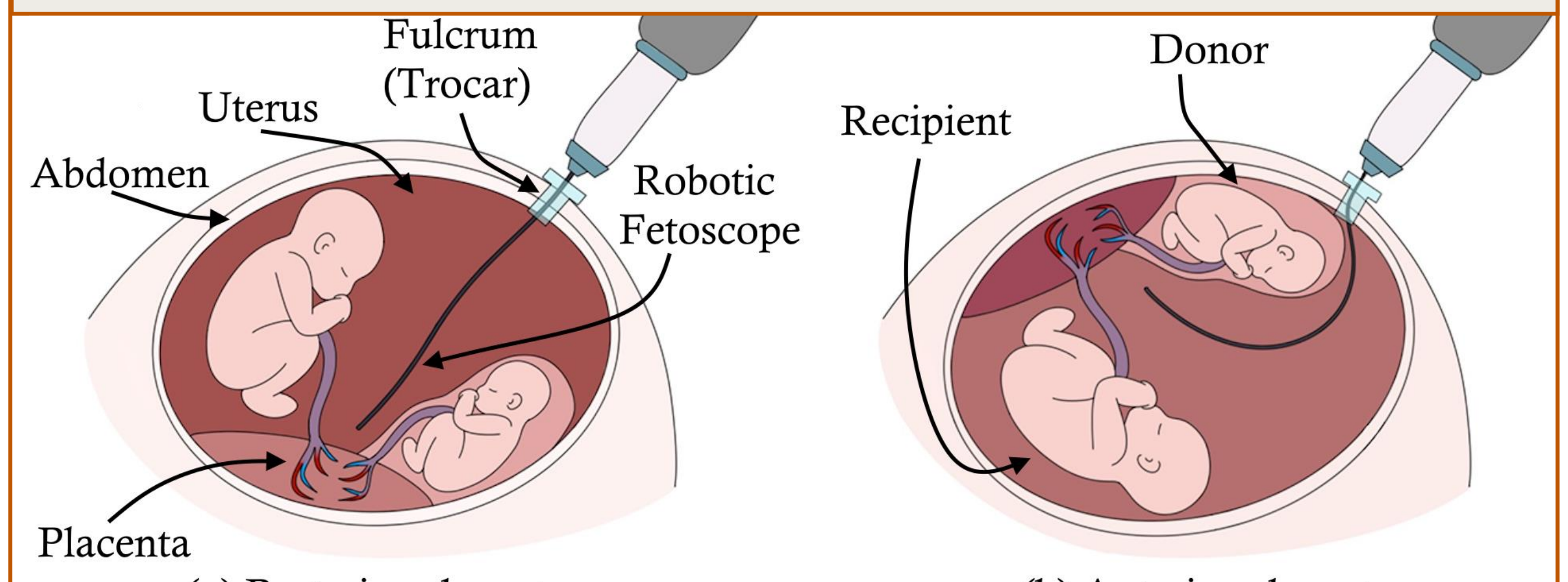
HEROLAB

Background and Motivation



(a) Posterior placenta (b) Anterior placenta

FIGURE 1: Illustration of the proposed robotic system, moving to the posterior placenta **(a)** and bending 180 degrees to reach the anterior placenta **(b)**.

Twin-to-Twin Transfusion Syndrome (TTTS) is a life-threatening condition that occurs in monochorionic twin pregnancies, where one twin receives more blood from the shared placenta, while the other twin receives less.

Fetoscopic laser photocoagulation (FLP) of the placental anastomoses between the twin circulations followed by the *"Solomon technique"* to connect the anastomotic sites is the standard of care for the treatment of TTTS.

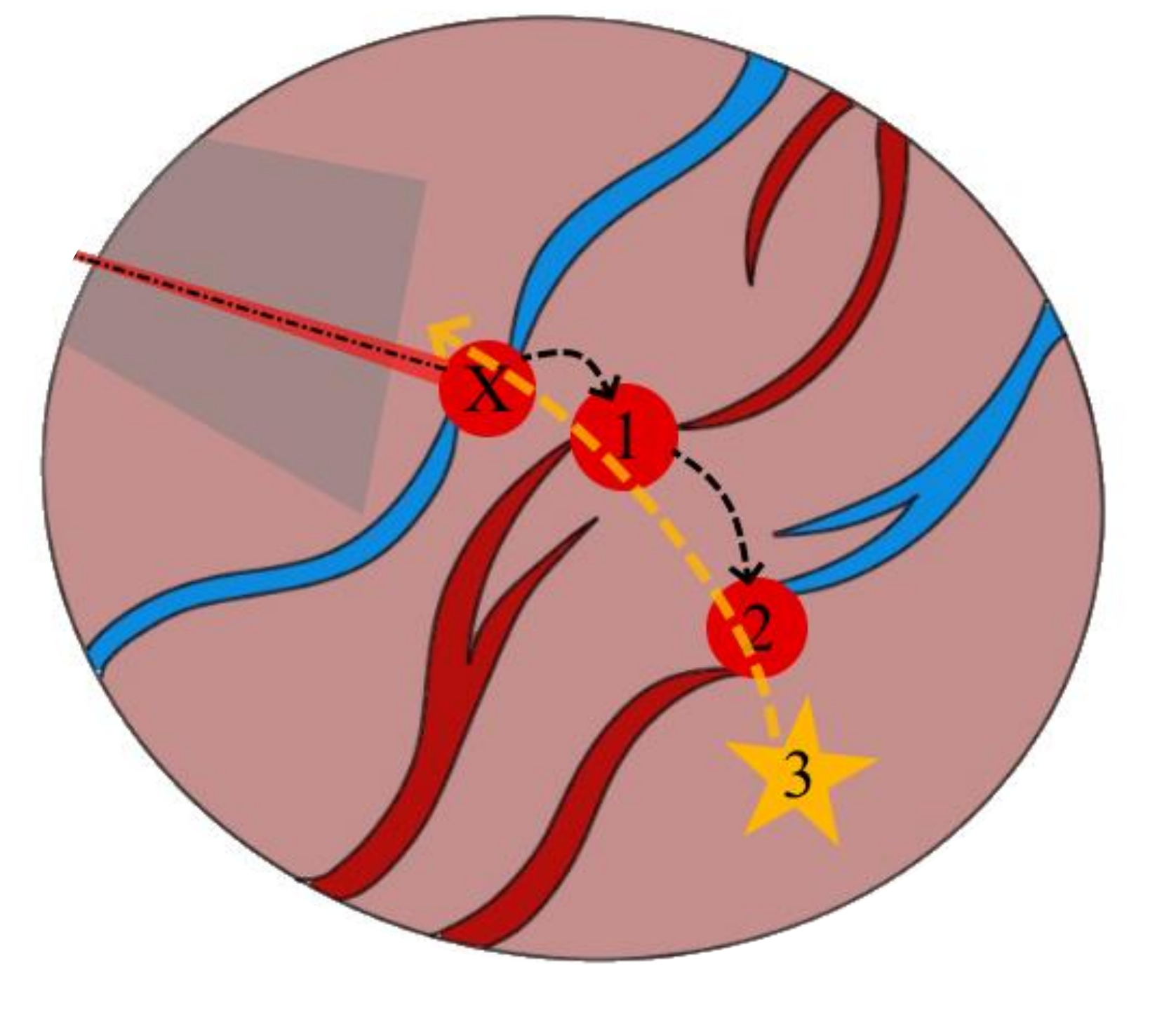
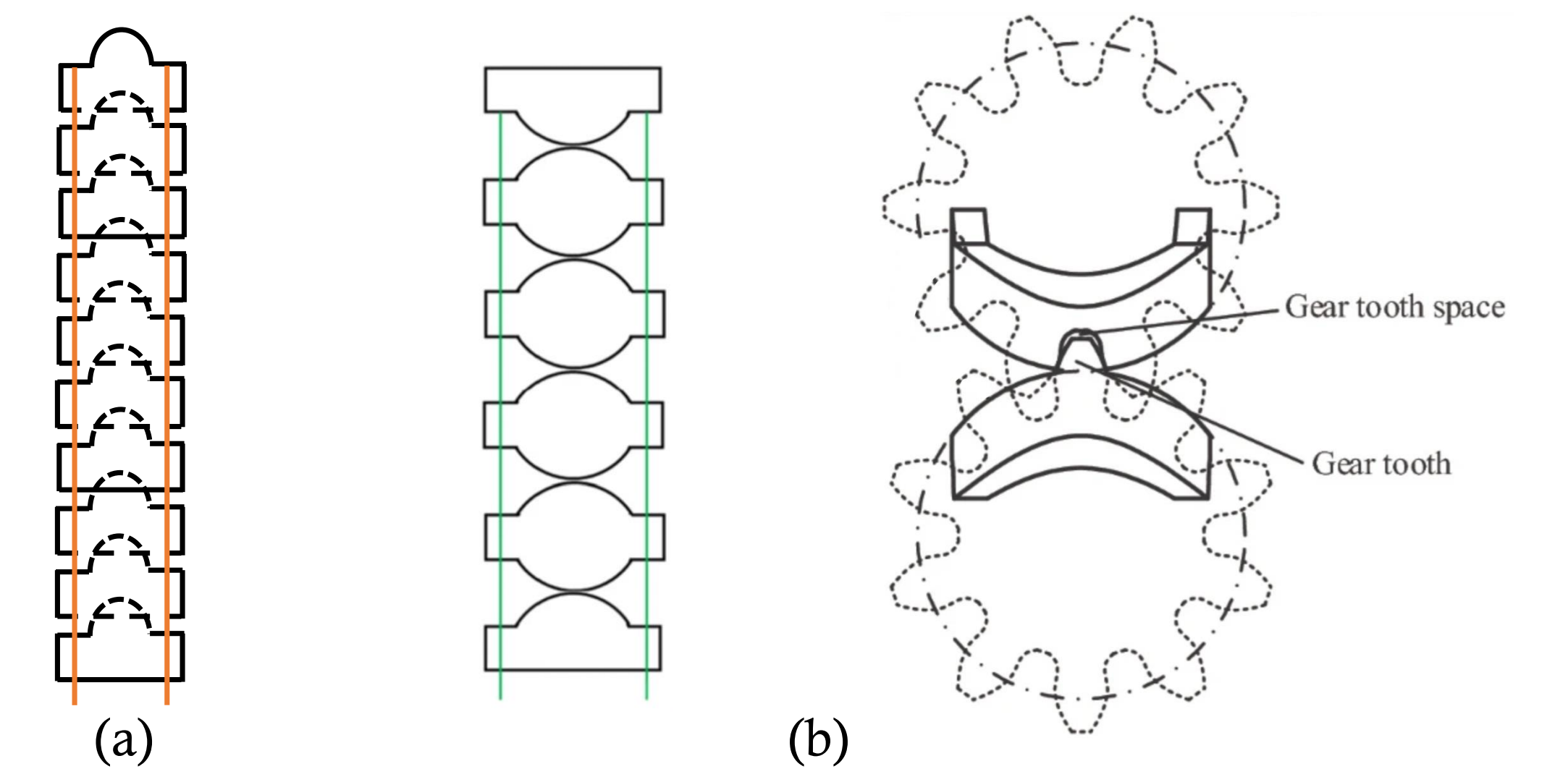


FIGURE 2: FLP and Solomon technique trajectory on placental anastomoses.

The baby can inadvertently grab the surgical instrument and twist it. Need a design to counteract the effect of the force and prevent tendon shearing in the manipulator.

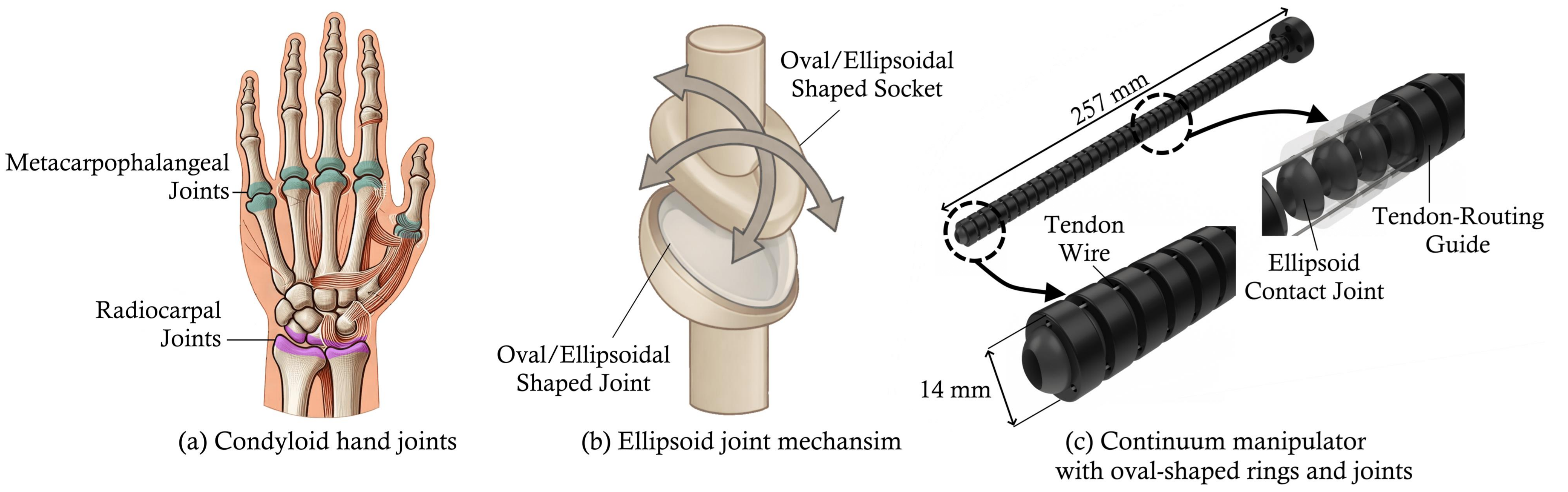


(a) (b)

FIGURE 3: Comparison of ellipsoidal design **(a)** and other rolling joint rings **(b)**.

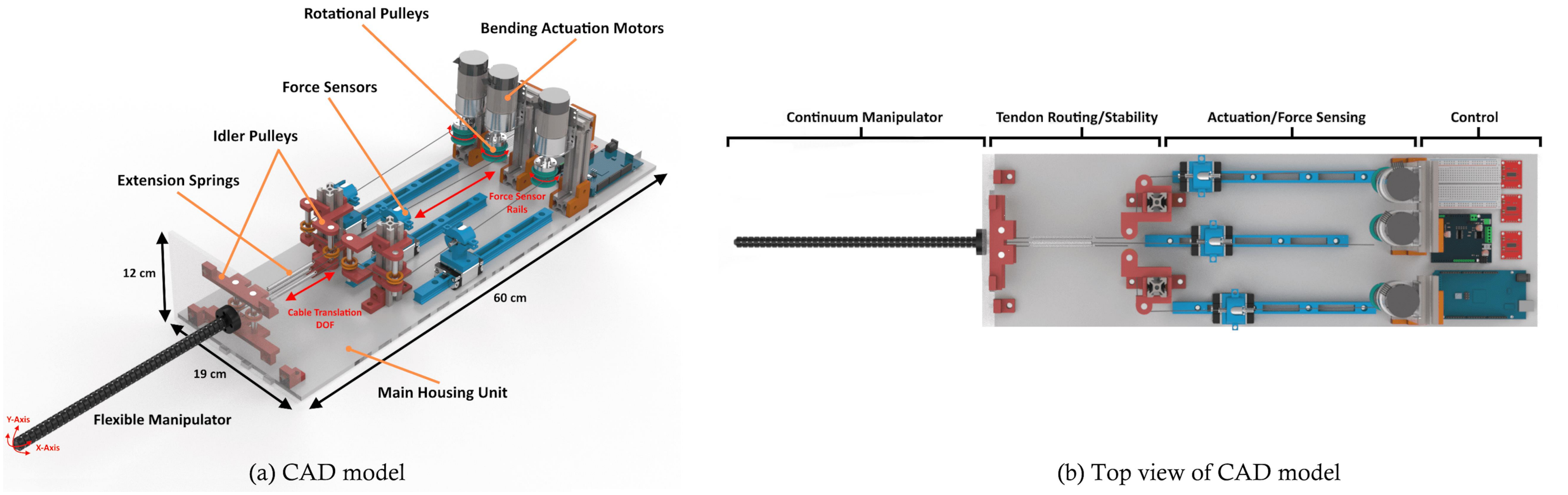
This research presents a novel continuum manipulator with (i) a flexion range of up to 230°, (ii) capability for omnidirectional bending, (iii) torsion prevention with its ellipsoidal ring shape, and (iv) a higher bending resolution and compliance compared to other rolling joint manipulators.

Bio-Inspired Design of Ellipsoidal Rings and Robotic System



(a) Condyloid hand joints (b) Ellipsoid joint mechansim (c) Continuum manipulator with oval-shaped rings and joints

FIGURE 4: Bio-inspired continuum design of condyloid hand joints.



(a) CAD model (b) Top view of CAD model

FIGURE 5: Computer-aided design (CAD) of prototype flexible robotic system.

- Inspired by condyloid joints in human hands, the ellipsoidal design introduces a kinematic constraint
- The rings constrain torsion and enables sliding and bending along both the x-axis and y-axis
- Tendon damage is prevented if the fetus grabs and twists the instrument
- Minimizes rolling joint slippage: lateral-slip, longitudinal-slip, and rolling-slip

Experimental Setup and Workspace Analysis Methods

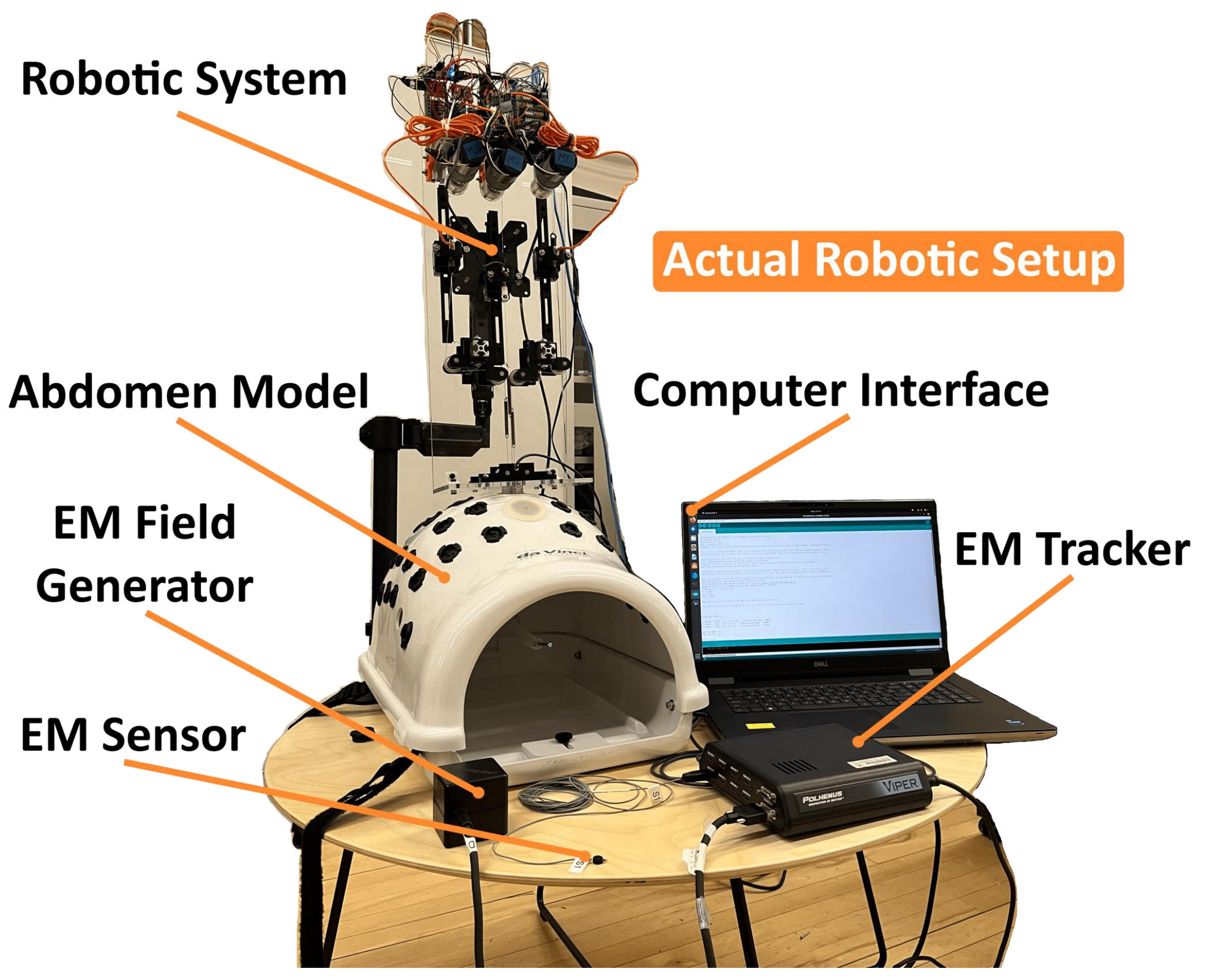


FIGURE 6: Experimental setup to track manipulator movement and bending in abdomen model using an EM tracker.

Euclidean distance between the center and a point (Eq.1)

$$d = \sqrt{(p_x - c_x)^2 + (p_y - c_y)^2 + (p_z - c_z)^2}$$

Volume of sphere (Eq.2)

$$V = \frac{4}{3}\pi R^3$$

Discriminant of quaternion components (Eq.3)

$$\Delta = q_w q_y - q_x q_z \quad (q_w, q_x, q_y, q_z)$$

Yaw (Eq.4)

$$\phi = \tan^{-1}\left(\frac{2(q_w q_z + q_x q_y)}{1 - 2(q_y^2 + q_z^2)}\right)$$

Pitch (Eq.5)

$$\chi = \sin^{-1}(2\Delta)$$

Roll (Eq.6)

$$\psi = \tan^{-1}\left(\frac{2(q_w q_x + q_y q_z)}{1 - 2(q_x^2 + q_y^2)}\right)$$

Bending Angle (Eq.7)

$$\theta = \arcsin(2(q_w q_y - q_x q_z))$$

Future Works

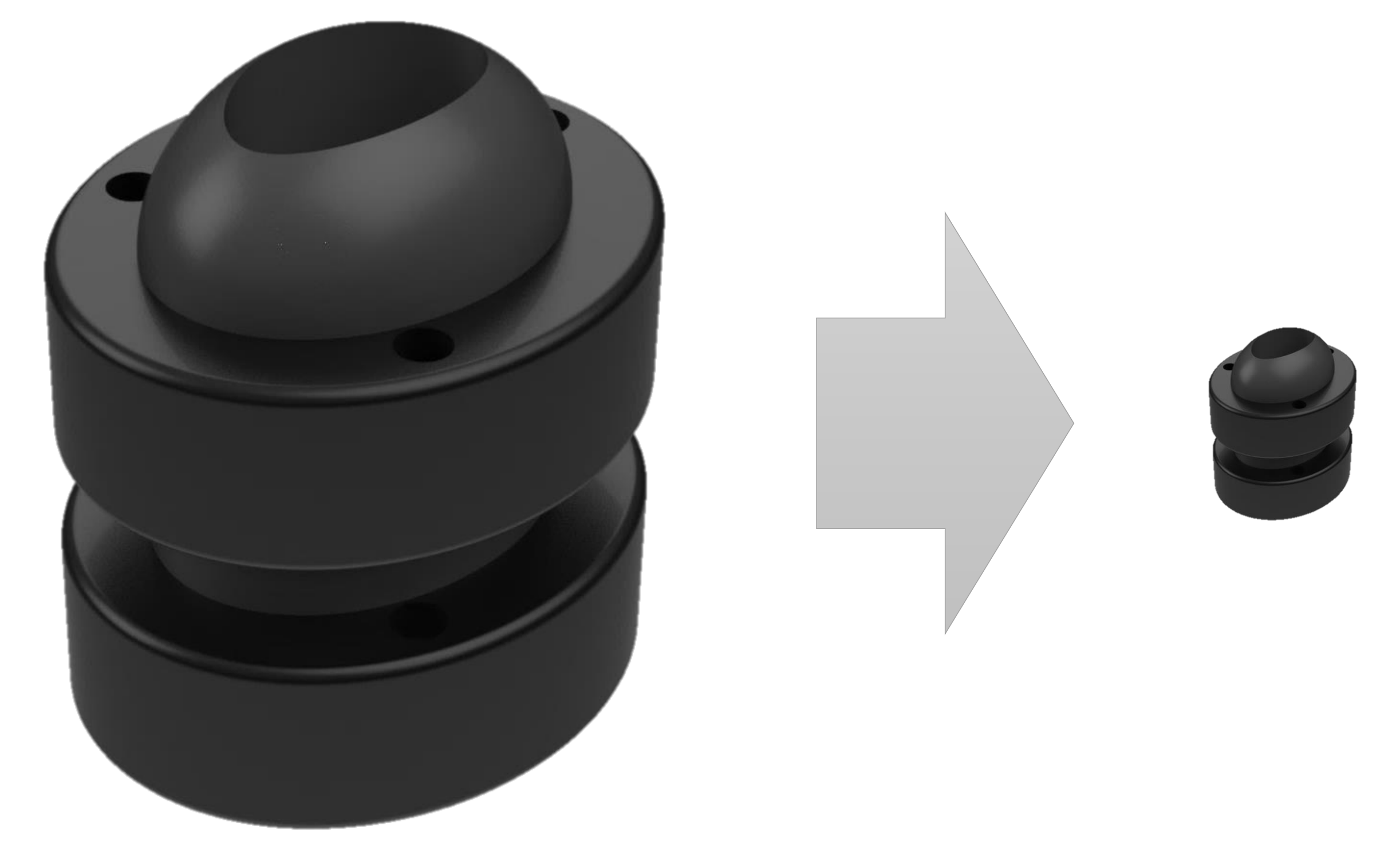


FIGURE 9: Rescaling continuum rings for miniaturization to fit a 10Fr trocar.

Directions	Plans and Goals
Mechanical Design	▪ Multi-lumen catheter backbone ▪ Cover exposed tendons ▪ Miniaturization
Modeling and Control	▪ Teleoperation ▪ Force control

Range of Motion Bending Experiment

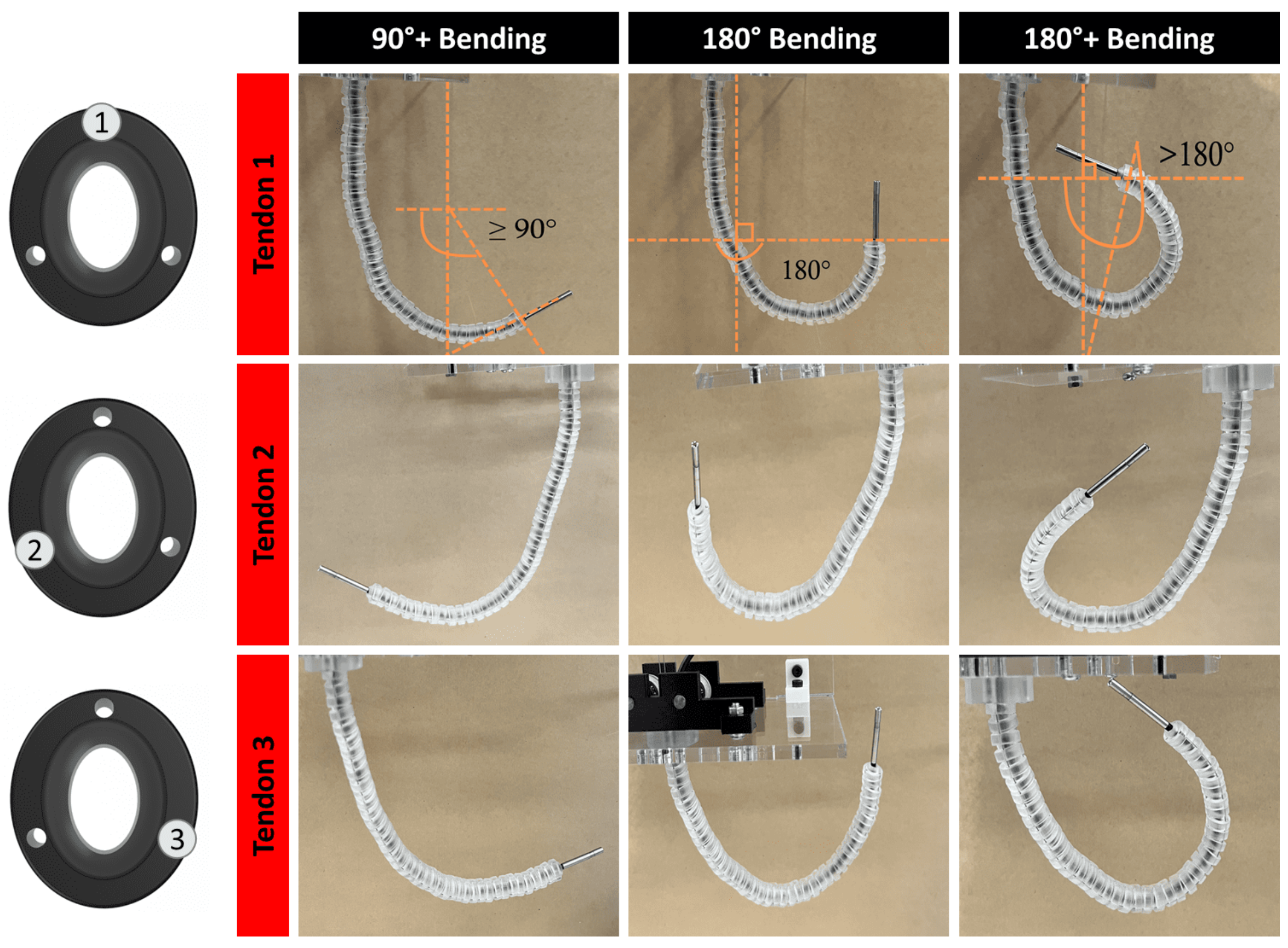
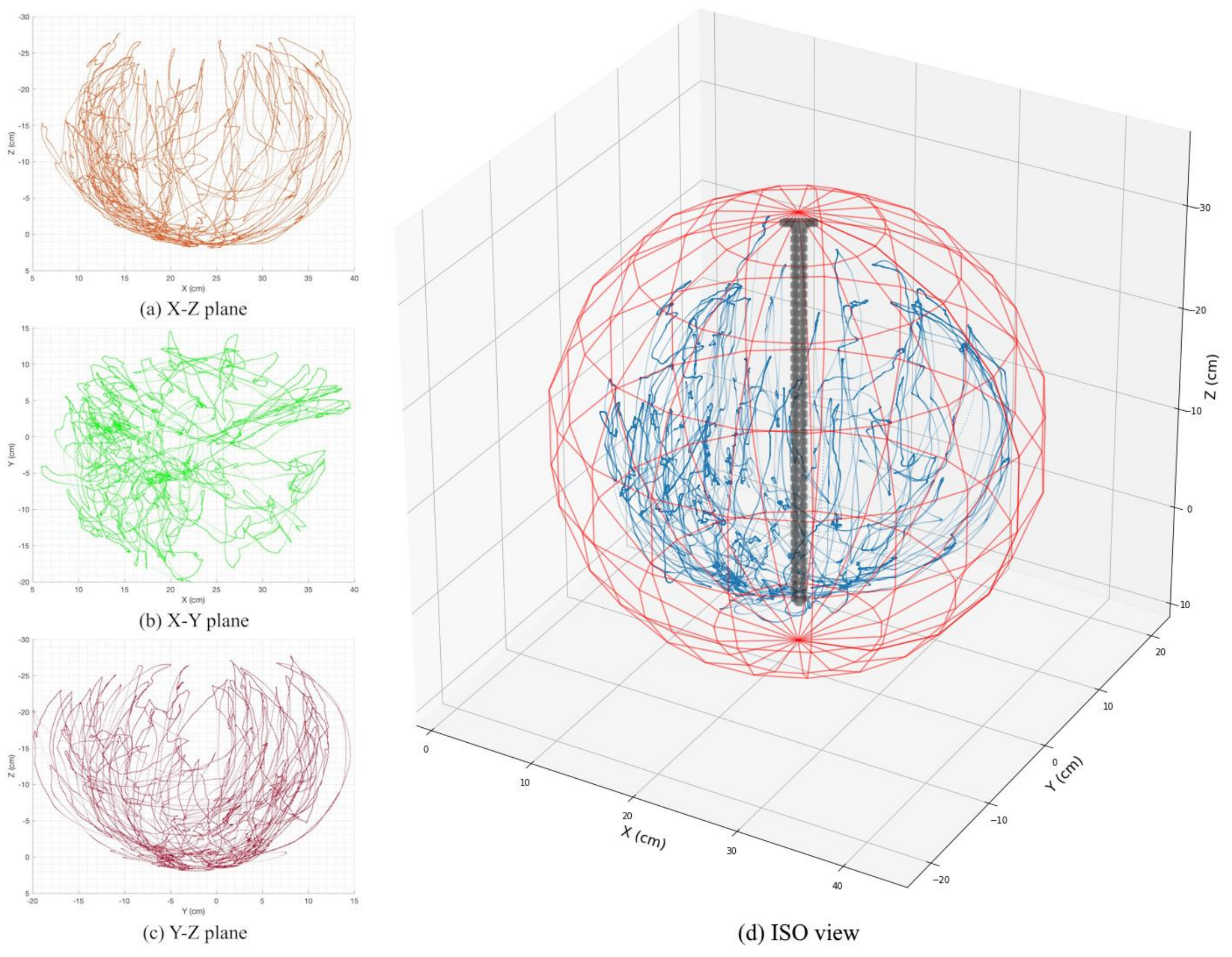


FIGURE 7: Bending experiment of ellipsoidal manipulator with each tendon pulled separately to achieve 90°, 180°, and the maximum bending angle.



(a) X-Z plane (b) X-Y plane (c) Y-Z plane (d) ISO view

FIGURE 8: 2D planar views of tracked trajectory **(a-c)** and 3D isometric view of robot volume workspace **(d)**.

- Maximum distance or radius calculated with Eq. 1 across all XYZ points from the EM data: **21.16 cm**
- Spherical volume covered by the current robot size: **39,685.84 cm³**
- Manipulator's full length from base to tip: **257 mm (25.7 cm)**
- Maximum bending angle achieved by the manipulator (using Eq. 7): **230°**
- Allows effective operation towards anterior placenta sites requiring more than 180° bending - Fig. 7 and Fig. 8 provide a clear visualization of the manipulator's volumetric workspace and bending capacity