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Design of a Rotatable One-Element Snake Bone for NOTES

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1 Background

Over the past decade, natural orifice transluminal endoscopic surgery (NOTES) has developed out of a merger of endoscopy and surgery [1]. NOTES offers the advantages of avoiding external incisions and scars, reducing pain, and shortening recovery time by using natural body orifices as the primary portal of entry for surgeries [2]. The NOTES platform consists of a flexible, hollow body—enabling travel in the interior of the human body—and the distal end (head), the mechanical structure of which is based off of the snake bone. After the distal end passes through a natural orifice, through a transluminal opening of the stomach, vagina, bladder, or colon, and reaches the target working place in the peritoneal cavity, several therapeutic and imaging tools can be passed through the hollow conduit of the NOTES' body for surgeries [3].

The traditional snake bone design presents two major problems. First, the movement is constrained to two bending degrees-of-freedom (DOF). A need to reorient the tool then often requires the entire body to be rotated by the physician, an unwieldly manipulation that both hinders convenience and results in imprecise control. Second, the traditional fabrication process is tedious and therefore lends to higher manufacturing costs; the bending joints must be first individually machined then assembled together piece-by-piece using rotation pins.

We propose a novel design for the snake bone that introduces an additional DOF via rotation and is simple and cost-effective to machine. The revised snake bone design features rotation segments controlled by wires that a physician can readily manipulate for increased control and convenience. Further, because surgical tools that pass through the NOTES body conduit are also installed on snake bone structures, the introduction of rotation to the snake bone design increases each tool's mobility and manipulation. This advance therefore presents the potential to decrease both the number of required tools and the overall diameter of the NOTES body. Finally, the body is machined as a single element and therefore minimizes the work of assembly.

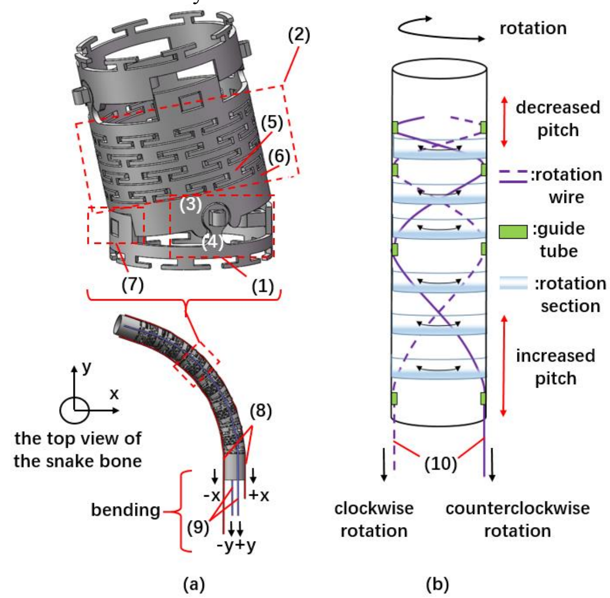

Fig. 1 Design of the rotatable one-element snake bone: a) one segment consists of pairs of bending hinges and a rotational section of "track-sled" rings and b) the rotational actuation of the snake bone.

2 Methods

The new design of the snake bone (Fig. 1) is explained in two separate sections of movement mechanism and actuation.

2.1 Design of bending and rotation mechanism. The rotatable one-element snake bone is machined from a single stainless steel tube 11.8 mm in diameter, 0.4 mm in thickness, and 125.8 mm in length. The various cuts form "hinge" pairs for bending (1) and "track-sled" rings for rotation (2) (Fig. 1a). The bending pair consists of a female hinge (3) and a male hinge (4), the rotation of which yields a bending of 15 degrees per pair. The rotational feature is made up of stacks of rings, each ring a series of tracks (female) (5) and sleds (male) (6) around the body circumference, yielding a rotation of 2 degrees per ring. The angular displacements of each of the hinge pairs and track-sled rings respectively sum to a designed total of 90 degrees of body bending angle and 62 degrees of body rotation angle. To avoid segments disconnecting during bending, the square pivot (7) is introduced to both sides of the bending pair to provide stability. To avoid risking the disconnection of segments during rotation, the number of track-sled pairs around a ring was increased, thereby decreasing slippage between segments.

2.2 Design of actuation mechanisms. Two pairs of wires (8) and (9) are threaded through small guide tubes positioned along the external wall of the body (Fig. 1a). Bending is achieved through pulling and releasing these bending wires. The rotation wires (10) are threaded through small guide tubes positioned along the internal wall of the body to form a helix with variable pitch (Fig. 1b). At the bottom of the snake bone, the pair of wires begins parallel to the axis to promote smooth pulling. The pair of wires turns up the body axis to form a helix of decreasing pitch towards the top of the snake bone, yielding increasing force for rotation and smaller sliding friction as the helix approaches the top. Pulling and releasing these rotation wires rotates the entire body.

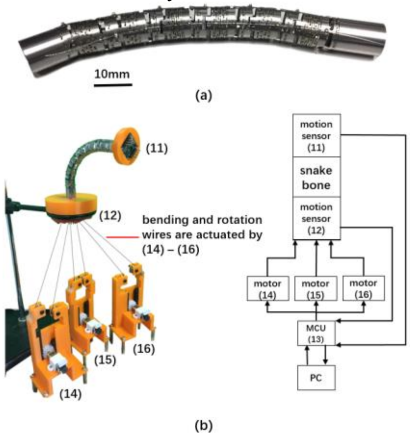

Fig. 2 Fabrication and validation: a) the machined snake bone is laser machined as one piece and b) the experimental set-up and schematic.

3 Results

The snake bone was machined by a laser cutter (StarCut Tube, Rofin CO., LTD, Germany) and the guide tubes were glued into the body structure (Fig. 2a). In order to evaluate the bending and rotation of the snake bone, a set-up was built based on Lei's geometric model [4] that proved a monotonic relationship between the inner bending radius and a certain bending angle. Two motion sensors (MPU-9250, InvenSense, Inc, San Jose, CA) (11) and (12) were attached onto the distal end and proximal end of the snake bone (Fig. 2b). The bending angle α and the rotation angle β are defined as the difference between the corresponding angles of the two motion sensors. The angular data was collected by a microcontroller unit (MCU, STM32F103ET, ST CO., LTD, Italy & France) (13). The angle and rotation wires were actuated by three DC motors (GM12-N20K, TT MOTOR (HK) INDUSTRIAL CO., LTD) (14) – (16) under the control of an MCU.

Two experiments were performed to evaluate the function of snake bone. The first experiment examined the rotation of the snake bone bent in three different angles: 0, 30, and 60 degrees. The second experiment examined the bending of the snake bone without rotation to ensure the alignment of the guide tubes. The pulling of wires was kept at a constant 7 mm/s and reached its maximum displacements in the first and second experiments at 4 mm and 7 mm respectively. Each experiment consisted of 10 trials, the averages of which are shown as single profiles (Fig. 3). The snake bone rotates up to 62 degrees for 0 degrees of bending (Fig. 3a). Increasing the bending angle increases the frictional forces the wire experiences, thus increasing the wire displacement needed for the same resultant body rotation. The bending profile (Fig. 3b) demonstrates the bending function of snake bone.

We asked the same labor to machine the traditional and one-element snake bones of the same size. It only took him 10 minutes to laser cut the one-element one. In contrast, he spent about 40 minutes to machining and assembling all the bending joints when making the traditional one. This rotatable snake bone thus presents potential to significantly cut down assembly time and therefore manufacturing cost.

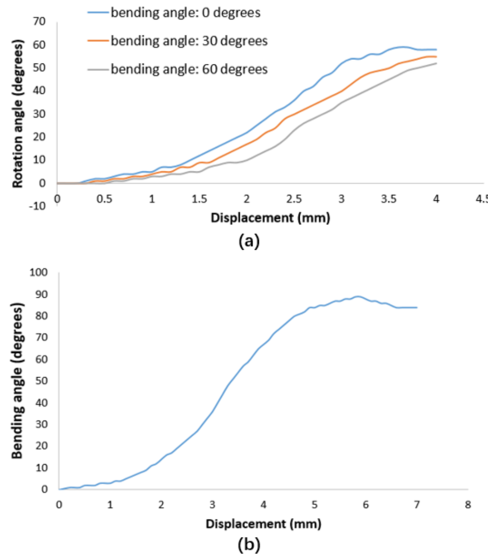

Fig. 3 Bend and rotation as a function of pulled wire displacement. The average of 10 trials is presented as a single profile. For clarity, bend and rotation only in one direction is displayed. Maximum body bending angle and body rotation angle is 90 and 62 degrees, respectively.

4 Interpretation

In this paper, we have presented the design, fabrication, and experimental validation and characterization of a novel snake bone for NOTES with both functions of rotation and bending. The body of this new snake bone can be machined as one piece using a laser cutting machine, obviating the need for manual assembly, and thus saving time and money. The bending and rotating functionality of the prototype was tested using a set-up of motion sensors and actuators. Future work will entail the design of rotation-agnostic bending, integration of the snake bone into the NOTES platform, and *in vivo* testing.

References

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