FINITE ELEMENT MODELING OF A LAYER JAMMING-BASED VARIABLE STIFFNESS MECHANISM FOR FLEXIBLE ENDOSCOPIC STRUCTURES

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2 Context

Minimally invasive surgery using endoscopic techniques is known to reduce complications during operations, promoting faster patient recovery, lower healthcare costs, and improved access to care. Technological advancements have further driven the growth of interventional endoscopy, with an annual average of 432,271 upper digestive endoscopic procedures performed in Belgium between 2013 and 2023 [1]. However, endoscopes are a known source of nosocomial infections due to their complex structure and internal channels. Traditional endoscopes consist of a long insertion tube with a lighting and visualization system, a working channel for surgical tools, and additional channels for rinsing, aspiration, or insufflation [2] (Figure 1). Their distal tip is controlled by cable-actuated mechanisms. Despite strict hospital cleaning protocols, some areas remain difficult to sterilize, allowing pathogens to persist and cause cross-contamination [3]. In 2019, these safety concerns led the U.S. Food and Drug Administration (FDA) to recommend using partially or fully disposable devices, initiating a shift toward single-use endoscopes [4].

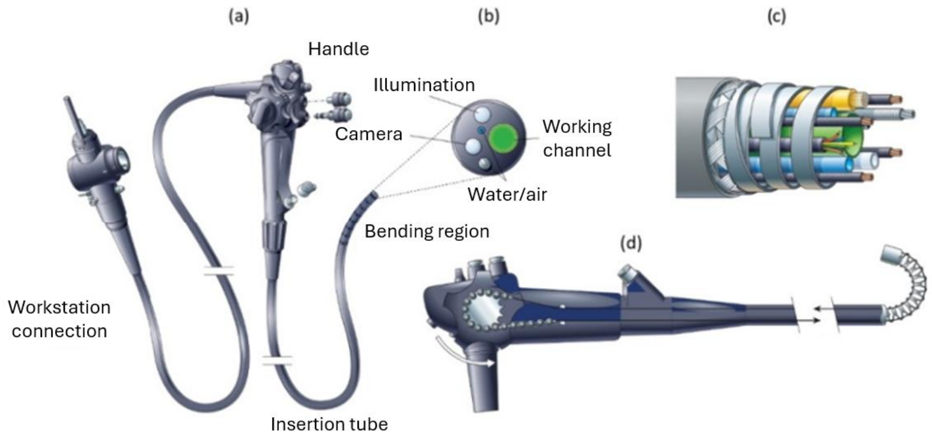

Figure 1 - Working principle of an endoscope. (a) General view. (b) Distal tip. (c) Composition of the insertion tube. (d) Cable actuation principle of the distal tip. Adapted from [2].

While disposable endoscopes reduce infection risks, they pose significant environmental, economic, and social challenges. A recent study [5] estimated that U.S. hospitals produce around 38,000 tons of waste annually from endoscopic procedures, a number that would increase by 40% if all procedures relied solely on single-use endoscopes. Of the 35% of recyclable endoscopic waste, only 9% is actually recycled, while the rest is incinerated (12%) or sent to landfills (79%). Another study [6] found that these devices generate approximately 15.78 tons of CO_2 emissions annually in the U.S. Beyond environmental concerns, disposable endoscopes are also costly in the long run [7]. Although their initial purchase price is lower, high usage volumes drive up expenses. To cut costs, manufacturers often reduce functionalities, potentially compromising performance compared to reusable models.

Given these limitations, single-use devices in their current form are unsustainable. To overcome these challenges, the BEAMS is developing a semi-disposable endoscope based on eco-friendly pneumatic actuation. As shown in Figure 2, this design will reduce waste by making only the insertion tube disposable (not possible with cable-actuated systems) while the control handle and workstation will remain reusable after basic cleaning, as they do not contact the patient. Additionally, the tube's design will optimize material use, enhance recyclability, and incorporate modularity for easier maintenance and repairs [8]. Beyond environmental benefits, pneumatic actuation can improve navigation through complex anatomical pathways while lowering the risk of patient injury, and enhance endoscopic localization capabilities by using MRI-compatible materials [9]. A previous study conducted within the BEAMS research group demonstrated the feasibility of this approach with a functional prototype [10]: a 90 cm-long, 5 mm-diameter steerable catheter made from a single material and capable of bending in all directions (Figure 3).

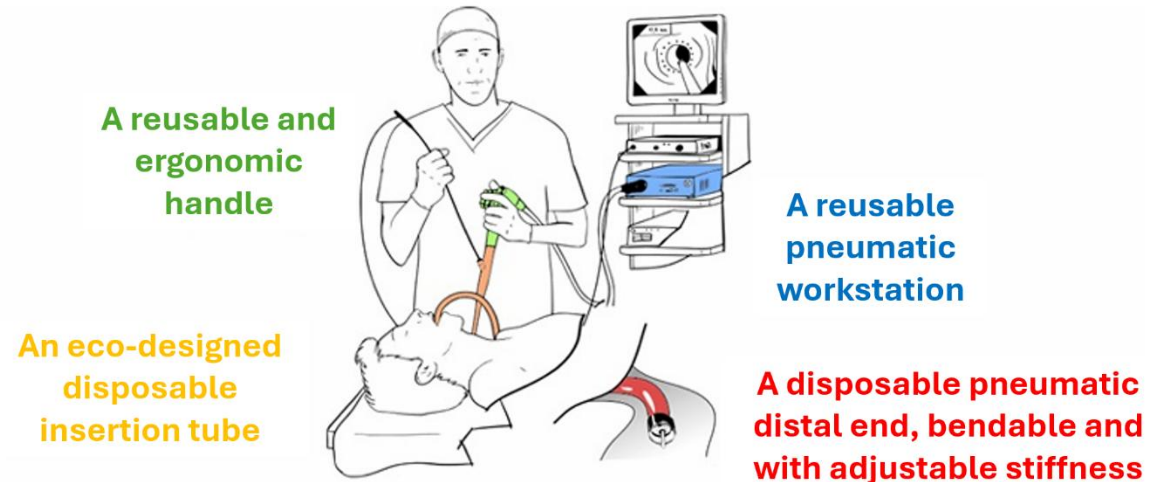

Figure 2 - Description of the eco-designed pneumatic endoscope solution

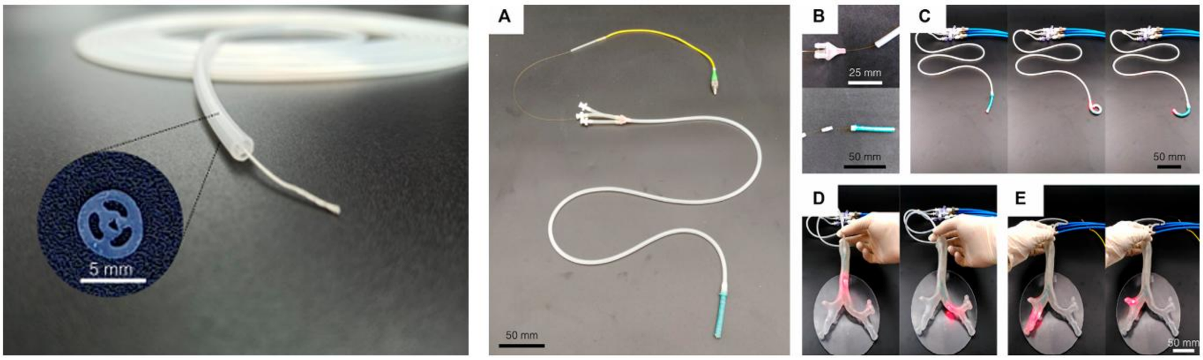

Figure 3 - Functional prototype of pneumatic catheter developed in [10].

3 Work

The soft nature of materials used for pneumatic actuation of flexible proximal sections in endoscopic devices creates certain limitations. Specifically, procedures such as biopsies are difficult to perform because the overly compliant structure does not allow for sufficient force application and lacks the stability necessary for precise operations. These limitations compromise the efficiency and accuracy of endoscopic interventions.

One promising solution to this limitation is integrating a variable stiffness mechanism into the flexible proximal section of the endoscopic device. Layer jamming is a particularly suitable approach. This technique modulates stiffness by compressing a stack of thin, flexible layers enclosed within an airtight membrane. When vacuum pressure is applied, atmospheric pressure compresses the layers together, increasing friction and significantly enhancing the structure's overall rigidity. Controlling the level of vacuum allows the stiffness to be adjusted in real time, enabling the structure to transition between a soft, compliant state and a stiffer one, more stable configuration based on procedural needs.

The objectives of this master thesis would be:

1) Conduct a comprehensive literature review on the principle and current applications of layer jamming.

2) Develop a finite element model to simulate the behavior of a layer jamming mechanism integrated into the flexible proximal section, focusing on how various parameters influence stiffness.

Optionally, perform experimental validation of the developed model to verify its predictive accuracy.

4 References

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