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Water jet actuation for ultra-low cost endoscopy: Characterization of miniature nozzles fabricated by rapid prototyping

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Abstract

Gastric cancer is the second leading cause of cancer death worldwide, accounting for over 10% of incidence cancers. Screening programs have been shown to be effective in reducing the mortality rate through early detection; however, many factors hinder the widespread implementation of these programs in low resource settings due to their high capital cost (associated mainly with cable driven units), limited portability, and reprocessing/contamination concerns. The Hydrojet endoscopic platform was developed as a low-cost alternative for gastric cancer screening in low-income countries. The capsule, completely made of bio-compatible plastic through rapid prototyping, uses pressurized water ejected from miniature nozzles to inspect the stomach. In order to achieve full controllability of the system inside the stomach, force characterization of the water jet actuators is needed. This work aimed to: i) characterize the relationship between thrust (with changes in outer diameter) and flow rate of miniature nozzles fabricated by rapid prototyping and ii) estimate the error due to the fabrication process. Results show that the experimental reaction thrust has a comparable trend to the analytical model hence a shape coefficient can be calculated and the actual thrust estimated at each point. Experimental results show the error due to rapid prototyping to be linear, thereby allowing for algorithmic compensation.

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Keywords: Capsule endoscopy; Gastric cancer screening; Robotic endoscopy; Nozzles characterization; Water-jet propulsion.

1. Introduction

Globally, gastric cancer accounts for 10% of incident cancers, with the fifth highest mortality rate among all cancers worldwide [1]. While gastric cancer is a global phenomena, more than 70% of incident cases are concentrated in low- and middle-income countries (LMIC) [2]. Endoscopic screening programs have been shown to be effective in reducing the mortality rate through early detection [3,4]. These programs are conducted at regional or urban medical centers using flexible endoscopes, which provide high definition video and a tool channel for interacting with the tissue (e.g.

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tissue biopsy, endoscopic mucosal resection (EMR)). After the use, the flexible endoscope needs to be reprocessed in order to be sanitized for the next procedure [5].

Despite the high incidence of gastric cancers, there are several barriers to traditional endoscopic screening in LMIC and remote locations. The high initial and repair costs of flexible endoscopes limit availability, and reprocessing requires specialized equipment and raises the cost-per-procedure. The limited portability of flexible endoscopes also limits screening to patients near regional or urban endoscopy centers. The limited availability in LMIC creates a need for alternative endoscopic screening technologies to address these problems.

In [6], the Hydrojet endoscopic platform was presented as a low-cost alternative for gastric cancer screening in LMIC and rural or remote locations. The Hydrojet is a soft-tethered endoscopic capsule whose movement is controlled by pressurized water (Fig.1). Three water jet actuators precisely carved inside the capsule body allow for camera movement to inspect the stomach. The main advantage of the platform is that, in contrast to the Bowden cable actuation used in flexible endoscopes, jet actuation allows for the manufacturing of a simple flexible tether which can be produced at a low cost (i.e., $2 per unit). In addition, the endoscopic capsule is made of bio-compatible plastic allowing for low-cost fabrication using rapid prototyping. This fabrication process, however, can result in errors especially for miniaturized devices. Force characterization of the water jet actuators is needed in order to achieve full controllability of the system inside the stomach.

This work examines in detail the fabrication process and the modeling/characterization of the nozzle profiles considering imperfection due to manufacturing by rapid prototyping.

2. Nozzles design and fabrication

Water jet actuation leverages a pressurized liquid ejected through propulsion nozzles to obtain thrust. The reaction thrust characteristic of a propulsion system has been extensively studied in the past [7,8]. However, there are no studies analysing the thrust characteristic of a miniature nozzle with curved profile fabricated by rapid prototyping (Fig.1). In this work, two internal profiles with different aspect ratio (A/R) were designed in order to quantify the relationship between reaction thrust and nozzle cross-sectional area under the condition of different flow rates. Each profile has an exponential convergence along the cross-sectional axis (Fig.1).

Considering the fluid conservation of mass and assuming a time invariant flow, the thrust depends uniquely on the internal geometry of the capsule jet as follows:

$$F = -\dot{m}(v_{in} - v_{out}) + \int_{A_{out}} p_{out} n \, dA_{out} \tag{1}$$

where $\dot{m}$ is the mass flow rate through the cavity, v_{out} and v_{in} the outlet and inlet velocity, p_{out} the pressure acting on A_{out} and n is the unit vector normal to the inner wall surface. The analytical model obtained by integration over the two different contours was then validated using experimental data. An upper limit pressure of 3 bar was implemented to prevent potential damage to the tissue [6].

The capsule prototype is presented in Fig. 1. The tridimensional model was implemented using Solidworks CAD software (Dassault Systems, France). The profiles were cut from the capsule internal body using a single sweep having the internal axis as a reference. The capsule was then fabricated using VeroWhite plastic material trough rapid prototyping (OBJET 30, Objet Geometries Ltd, USA). Cleaning procedures aimed at removing the support material from the printing process were then performed. This procedure consisted of leaving the nozzles for 6 hours in a bath composed of 5g of sodium hydroxide dissolved in 200ml water and then removing the remaining support material using pressurized air at 3 bar for 1 min.

3. Results and discussion

The experimental testing aimed to: i) characterize the relationship between thrust (with changes in outer diameter) and flow rate and ii) estimate the error due to rapid prototyping. Experimental trials were performed with the custom test bench shown in Fig.1. Each jet was attached to a metal beam held in vertical position using a multi-purpose metallic arm. A 3D-printed holder connects the beam to the Force/Torque sensor (Nano17, ATI Industrial Automation,

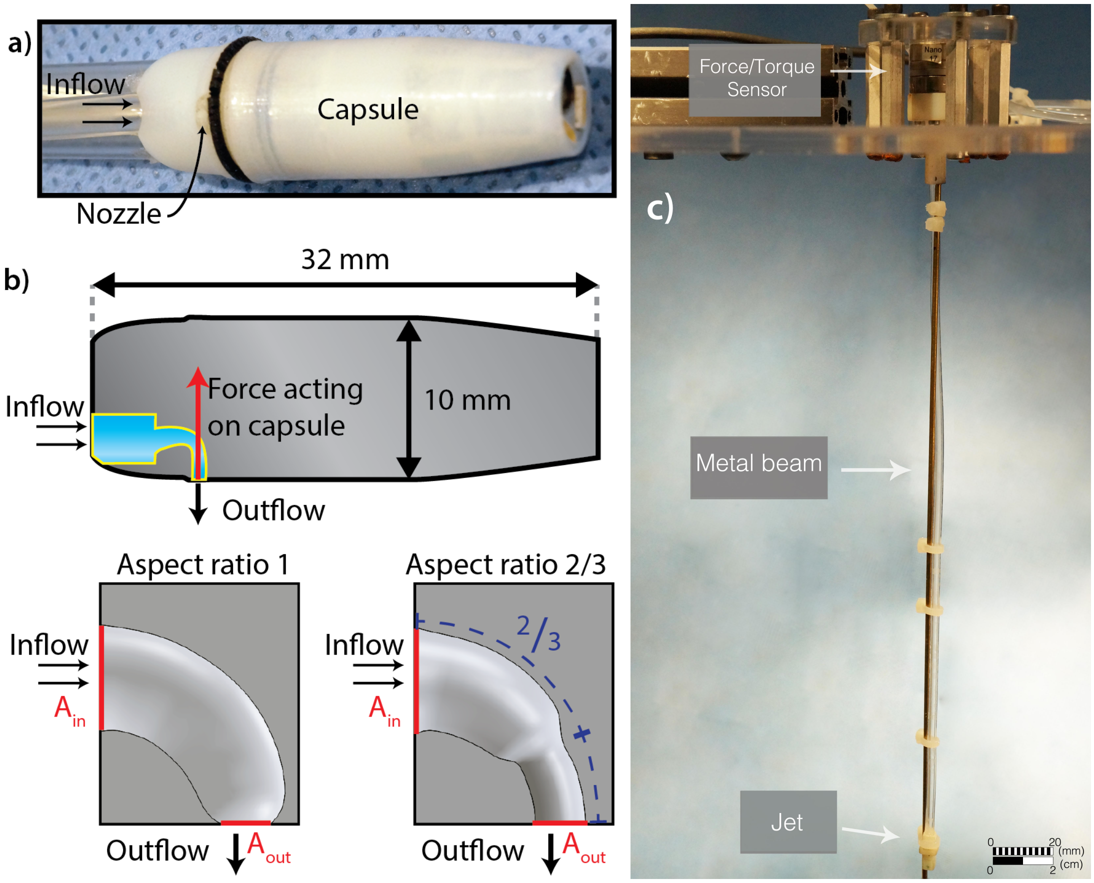

Fig. 1. a) Capsule prototype, b) Model cross-section and nozzle profiles with different aspect ratios (A/R), c) Custom bench test composed by an ATI Nano17 Force/Torque sensor with a nozzle attached on the distal tip.

USA) that is fixed on the arm. Pressurized water was provided to the proximal opening of the jet using a PVC plastic tube (Shore hardness A90, 1.6mm inner diameter) before being expelled out through the smaller external opening. In order to compare the two different shapes, the upstream pressure was fixed at 70 psi and the flow was controlled using a fixed-step valve.

The average of three experiments on the same profile, for each different A/R and diameter, was compared to the analytical model in order to find a shape calibration coefficient (Fig.2). The results show that the experimental data follow the general thrust equation trend thus the actual thrust can be calculated at each time.

In order to understand the error due to rapid prototyping, the same nozzle profile was fabricated five times and the data was compared to obtain the absolute and relative error of the process (Fig.2). The maximum absolute error is 10 mN obtained for an effective thurst of 70 mN. This correspond to a relative error of 18% with respect to the average value. However, these plots show that the trend due to the process is linear, thereby allowing for easy compensation and effective thrust estimation at each time.

4. Conclusion

This paper describes the characterization of miniature nozzles fabricated by rapid prototyping. Two different nozzle shapes were studied and showed that with a fixed upstream pressure, the outer diameter of 0.75mm achieved higher thrust compared to the 0.55mm. The aspect ratio did not affect the trust, and likewise the fabrication process added only a constant error that can be easily compensated. The implementation of a nozzle throttle control can be then obtained using the shape coefficient to find the actual reaction thrust acting on the capsule. The nozzles

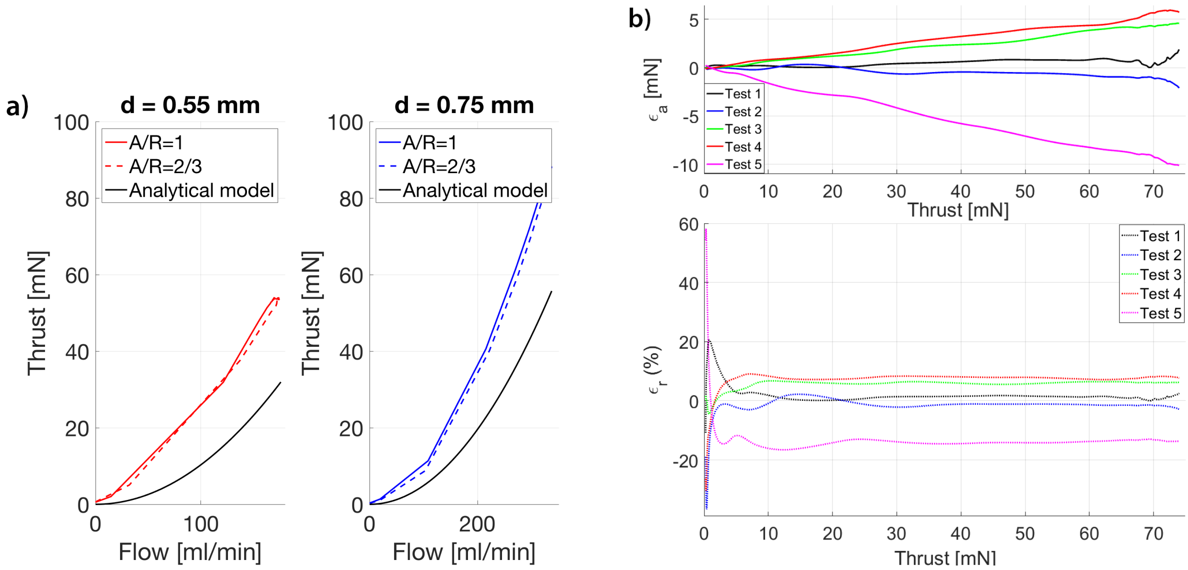

Fig. 2. a) Average measured thrust on five experiments with different A/R, compared with the analytical model with outer diameter (d) and inner diameter (1.6mm). b) Absolute (ϵ_a) and relative (ϵ_r) error due to rapid prototyping calculated with respect to the average thrust. $\epsilon_{ai} = F_i - \mu_i$; $\epsilon_{ri} = \frac{F_i - \mu_i}{\mu_i}$ where F_i is the i-th thrust sample and μ_i is the i-th average thrust value.

characterization is the first step towards a closed loop control of the Hydrojet capsule based on the reaction force. This information can be added to a tether model to estimate the position of the capsule inside the stomach.

In conclusion, the Hydrojet addresses barriers to traditional endoscopic screening in LMIC through the targeted design of a portable system for upper GI cancer screening. With the success of medical trials, the Hydrojet platform can address a deficiency in point of care medicine in LMIC.

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