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A tribological investigation of the small bowel lumen surface

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ABSTRACT

Robotic capsule endoscopy (RCE), where a robotically controlled capsule endoscope is used to navigate the gastrointestinal tract, is a developing technology currently hindered by mobility challenges within the small bowel. This research seeks to engage the frictional characterization of the small bowel with a formally designed experiment which samples the variability within the porcine animal population while parameters such as engineering material, contact area and bowel region were varied. Friction force measurements were collected within an environmental chamber which closely simulates *in vivo* conditions. The results indicate that micro-patterned polydimethylsiloxane (PDMS) yields a statistically significantly higher coefficient of friction (COF) than stainless steel or polycarbonate. The effects of contact area and bowel region vary across the porcine animal population. The COF under these conditions ranged from 0.0004 to 0.018.

1. Introduction

Broad challenges exist when designing studies to characterize biological tissue and the small bowel is no exception. One goal of this study was to estimate the amount of tribological variability which could be attributed to the random sampling of a porcine population. Further, we looked to evaluate the variability that existed within proximal, middle and distal portions of the small bowel tract. While controlling this factor, we measured the friction forces present between the lumen surface and prospective robotic capsule endoscope (RCE) body materials such as polydimethylsiloxane (PDMS), stainless steel and polycarbonate as contact area was varied.

This work has applications in capsule endoscopy (CE) and is specifically motivated by efforts to optimize the mobility of a RCE. CE is an effective diagnostic technology employed within the gastrointestinal (GI) tract which may lead to improvements in discovering, treating or removing pathologies which manifest in the small bowel [1–10]. If effective, independently mobile RCE's could build upon the capabilities of existing endoscopic techniques, which have limitations such as risk of GI wall perforation and tether length, and expand the role of passive capsule endoscopes in GI tract treatment.

2. Background

Current limitations to RCE mobility within the bowel include traction manipulation due to the presence of complex lumen surface features and a highly motile, tortuous intestine path. Not only are the surface interactions with the bowel surface complex, an RCE must also overcome a variety of forces which will be working to move the capsule along the length of the GI tract. These forces include the peristaltic wave contractions and myenteric contractile forces from the intestinal wall, as well as mucoadhesion, or the energy required to separate the collapsed lumen, and friction between the capsule surface and intestinal wall [11,12]. The surrounding organs, weight of the intestinal wall and pressure from the fluid within the bowel also impart forces on the RCE, in addition to gravity, which acts as a body force QUOTE Friction forces, including dry contact between the tissue and RCE surface as well as fluid shear act in opposition of the RCE's movement.

Experimental data relating to the aforementioned measured forces is often specific to test capsule geometry and is primarily obtained under *in vitro* conditions [11–26]. Biaxial stress measurements have been collected as well as myenteric contractions and show small bowel to be viscoelastic with time dependent stress and strain [11–15]. Friction forces have been measured and the published values are highly variable based on a number of parameters, such as the material in contact with the tissue, capsule geometry and weight, contact area and speed [11,15–23]. It is suspected that each of these parameters affects the tissue's friction response to a different degree. Material coupons from other work have primarily included aluminum (not a viable surgical tool or medical device material) and ABS

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plastic, but ranges from acrylic to copper to polymeric tubing [15–18,20,21]. Several groups have studied the effects of varying capsule diameter, length and surface features to discover that the capsule diameter has the most significant effect, when evaluated within a closed bowel specimen [15,16,18]. Surface features also lead to increased friction resistance, though it is not understood whether surface area versus surface geometry has a greater impact on this outcome [16]. The contribution of weight was shown by Kim et al., to have a positive influence on the friction force, but an inverse relationship to the coefficient of friction [15]. However, other researchers have not seen significant effects from weight relative to other parameters, especially when considering small magnitudes of weight, like that expected of a typical RCE [18]. Several studies, that include the work of the authors, have measured increased friction forces with larger sled velocity [15,17,18,24].

Friction manipulation is currently one of the primary obstacles to initiating and controlling endoscopic capsule movement. Knowledge of the static and dynamic friction forces that the robot will encounter during initiation of movement and subsequent locomotion is of utmost importance. By identifying which parameters can be dynamically manipulated along the length of the small bowel, a well-designed RCE can work with or against the friction as needed for movement or positioning. It is the frictional properties of this mucosal surface that this research intends to examine. Small bowel tissue from three porcine subjects was collected and tested upon three test materials with two different contact areas. The test materials were selected based on their potential as RCE materials. Specimens from the proximal, middle and small bowel were tested. In addition to seeking data specific to the authors' RCE design, this research also seeks to account for and quantify the variability inherent in biological tissue, under frictional testing conditions.

3. Experimental methods

A novel tribometer device used in previous research was utilized for this study with minor modifications [24]. To summarize, a linear stepper motor (Haydon-Kerk, 25844–05–001ENG) translates a load cell (Loadcell Central, ESP4–1KG) along a linear slide. Attached to the load cell by a string is a tissue fixture, which translates upon a fixed test coupon. A motor driver (Sparkfun, A3967), data acquisition system (National Instruments, myDAQ) and bridge strain measurement module (National Instruments, USB-9237, USB-9162) control the motion of the sled and record force over time. A schematic of the tribometer is shown in Fig. 1.

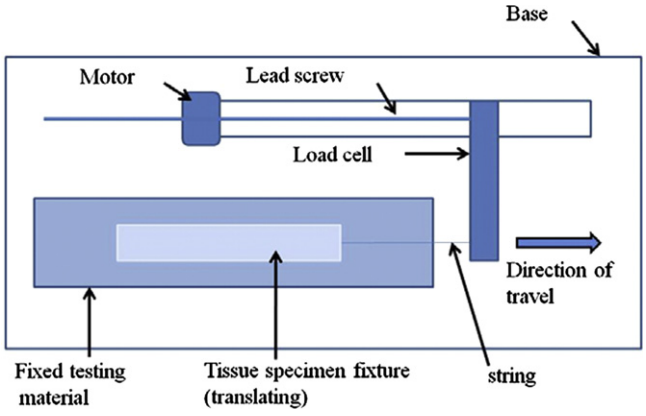

Fig. 1. Schematic of tribometer setup with tissue specimen fixture is pulled over a fixed test material.

To more closely approximate the climate *in vivo*, an environmental control chamber was designed and fabricated. The environmental control chamber was designed with the ability to add heat and humidity to a closed system, within which the tribometry experiments were conducted. The control chamber housed the tribometer, three heaters and water reservoirs. The heaters were mounted on three of the vertical walls and the water reservoirs were placed directly underneath. The custom heaters consisted of Nichrome wire wrapped around an electrically insulated frame to which a small fan was mounted. Electrical current input to the Nichrome wire was controlled so that the temperature within the chamber was held to $37.5 \pm 0.5\ ^{\circ}C$. Voltage control over the heater fans (passing warm air over the water reservoirs) maintained $95 \pm 3\%$ relative humidity within the chamber. A Solidworks CAD model of the tribometer within the control chamber is shown in Fig. 2, as is a photograph of the actual chamber. (The tribometer and water reservoirs are not visible in the photograph, due to obstruction from the opaque glove access holes.) An image of the tribometer inside the control chamber is shown in Fig. 4.

Porcine small bowel tissue from three animals was collected for this study. In order to reduce the amount of food debris within the bowel, the animals were placed on a Jell-O diet starting 48 h prior to the surgery, replaced with Gatorade for the final 24 h. Prior to euthanization, each of the animals had undergone a surgical procedure (during a surgical resident training). The surgery performed on Pig 1 was unknown, but it had no visible gastrointestinal trauma. Pig 2 underwent a gastric bypass. Pig 3 also underwent a gastric bypass and had visible thoracic trauma. Small bowel was excised from the animals immediately following euthanization and stored in a lactated Ringer's solution at 3 °C for no more than 24 h prior to testing. When exposed to unconditioned air, tissue drying has been observed and previously remedied by applying saline to the tissue surface [11,18,24]. We speculate that the addition of saline may have adverse outcomes on the friction measurements. To prepare for testing, the chamber was first heated and humidified to the aforementioned specifications. The unprepared tissue, preserved in a Ringer's solution, was placed within the chamber where it slowly equilibrated to *in vivo* temperature and humidity over a period of approximately 90 min. All tissue preparation and testing was then performed within the chamber, accessed via air-tight glove holes located on the front of the chamber. No external lubricant was added to the tissue surface during testing. Therefore, the test was conducted with only the native mucus serving as a lubricating layer. The test materials were wiped clean between each test.

For this study, the test material was fixed to the tribometer base while a porcine bowel specimen was clamped into a fixture with a protrusion of prescribed contact area and translated horizontally up the testing material, which is shown Fig. 3. This allows for testing without a leading sled edge, which essentially "normalizes" the COF to be independent of sled geometry. Previous work indicates that sled edge effects appear to introduce an additional variable which increases COF by over one order of magnitude as compared to measurements collected using an overhanging sled with negligible edge effects [24]. To prepare for mounting, the tissue specimen was placed upon the protruding fixture and a plate with a cutout was placed upon the tissue and held gently in place by magnets to the front and rear. The magnet strength was selected so as not to unnecessarily compress the unexposed tissue. Every effort was made to avoid undue tissue strain during the mounting process. This was visually verified by the presence of small "wrinkles" on the tissue surface. The authors recognize that it is possible the mounting process induced strain to the tissue. It is plausible that this state of stress may be a more natural representation of the tissue