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Modeling and *In Vitro* Experimental Validation for Kinetics of the Colonoscope in Colonoscopy

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Abstract

Colonoscopy is the most sensitive and specific means for detection of colon cancers and polyps. To make colonoscopy more effective several problems must be overcome including: pain associated with the procedure, the risk of perforation, and incomplete intubation colonoscopy. Technically, these problems are the result of loop formation during colonoscopy. Although, several solutions such as modifying the stiffness of the colonoscope, using an overtube and developing image-guided instruments have been introduced to resolve the looping problem, the results of these systems are not completely satisfactory. A new paradigm to overcome loop formation is proposed that is doctor-assistive colonoscopy. In this approach, the endoscopists performance is enhanced by providing using a kinetic model that provides information such as the shape of the scope, direction of the colon and forces exerted within certain sections. It is expected that with the help of this model, the endoscopist would be able to adjust the manipulation to avoid loop formation. In the present studies, the kinetic model is developed and validated using an *ex vivo* colonoscopy test-bed with a comprehensive kinematic and kinetic data collection. The model utilizes an established colon model based on animal tissue with position tracking sensors, contact force sensors for the intraluminal portion of the scope and a Colonoscopy Force Monitor for the external insertion tube.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

Keywords

Colonoscopy; Contact force; Frictional force; Kinetics; Porcine colon

INTRODUCTION

Colonoscopy is the most effective way to examine the colon and rectum for a broad array of disorders from inflammatory to malignant diseases. Not only is it a useful screening and diagnostic tool, but it also provides the possibility for intervention such as removing premalignant polyps. In the 40 years since 1971 colonoscopy was first described, significant technical advancements significantly increased its functionality. Nevertheless, depending on training and experience failure rates may be as high as 10%. The most important technical factor contributing to the failure to complete a colonoscopy is the inability to manage loop formation. Looping of the colon increases the need for pain control and likely increases the risk of perforation.^{4,7} Several designs to overcome loop formation have been introduced to clinical practice including over-tube colonoscope, variable stiffness colonoscope, image-guided scopes and self-propelled instruments, but results of these systems are not entirely satisfactory. In general, the existing solutions of loop problem can be categorized into the following groups: (1) fully automated system: autonomous endoscope. The drawback and challenge of this idea have been discussed extensively. The major drawback for robotic colonoscopy is diminished insertion time. Furthermore, autonomous locomotion in colon has not proved to be effective because of the highly complexity of the anatomy of the intestine system because the geometry of the colon differs significantly among individuals. (2) image assisted system: 3D configuration of looping on real-time. This approach helps endoscopists by providing real time information of looping in human body; however the system is expensive and somewhat cumbersome because of the need for magnetic field sensors. (3) mechanical assisted system: varying the stiffness of the insertion tube or the use of an overtube has the potential to reduce looping by changing the conformation of the instrument and the colon loop. However, overtubes may increase the risk of perforation and changing the stiffness is often only useful after the scope has been straightened and is then advanced. Although alternatives for contemporary colonoscopy such as virtual colonoscopy exist they still have limitations. The virtual colonoscopy can detect only polyps >5 mm and misses diseases with color variation symptoms all together. Thus, the limitations on colonoscopy may be significantly reduced if the operator is given additional information such as the shape of the scope and forces exerted by certain sections of the instrument. This information could make the contemporary scope “smart” in the sense that it avoids loop formation by optimizing operation. In order to make a passive scope become a “smart” active scope without additional aiding equipment an accurate mathematical model of colonoscopy in colonoscopy is necessary. The mathematical model of the colonoscope in colonoscopy must provide enough information to explain the relationship between the instruments motion and external force/torque. More specifically, the kinetic model must predict looping in real-time and provide data on the interactive forces between the insertion tube and the colon.

Cheng *et al.*^{3,5} pointed out an important engineering concept called “self-locking” mechanism which is relevant to the loop formation in colonoscopy. The interactive force between the colon and the scope is high complex due to frictional contact between two deformable objects, where the distal end of the scope remains stationary and does not move forward when the friction angle is greater than the driving force angle so that the loop of the scope in sigmoid colon will form largely. In this case, with the guidance from the mathematical model, endoscopists can adjust the position and orientation of the distal end of the scope at the control unit, and then apply the proper magnitude of external force and

torque to resolve the loop of the scope. Such optimal operation of the procedure must be aided by the mathematical model. This method is called a doctor assistive colonoscopy based on the mathematical model. Therefore, a doctor assistive colonoscopy based on the mathematical model could help endoscopists manipulate the scope more effectively and safely navigate complex loop configurations.

The significant interactive forces between the insertion tube and the colon is the primary reason of the risk of perforation, however it is difficult for endoscopists to manage the threshold force that cause colon's perforation if without the warning. With the help of mathematical model the interactive forces between the insertion tube and the colon can be calculated in terms of the external force/torque, the warning will be given to the endoscopists once the contact force is beyond the threshold force that would cause the perforation of the colon tissue. In this sense, the mathematical model can prevent the perforation of the colon in the colonoscopy.

The mathematical model of the colonoscope in colonoscopy also is essential to facilitate further design of the colonoscope. Clearly to design a controller and set its parameters it is critical to have an accurate mathematical model of the colonoscope in colonoscopy.

In this paper, we developed a kinetic model based on finite element method (FEM) to reflect the relationship between the input (the endoscopist's external operation) and the scope's motion. The contact force with frictional force between the insertion tube and the colon is computed by complementarity formulation, i.e., contact force computation is formulated into a linear complementarity problem (LCP) by linearizing Signorini's problem while the stiffness of the colon is computed based on Timoshenko's beam theory, i.e., the stiffness matrix of the colon is formulated in terms of a hollow cylinder beam with length, thickness and radius and its elasticity. In order to validate the mathematical model of the colonoscope in colonoscopy we built an *ex vivo* colonoscopy test-bed with a comprehensive kinematical and kinetic data collection, i.e., human-based "colon tray" with an animal tissue with position tracking sensors and the contact force sensor for the scope, CFM for the proximal end of the scope. Experimental results have a satisfactory agreement with model simulation results.

MATERIALS AND METHODS

Kinetic Model of the Colonoscope

The structure of the colonoscope is a long and slender deformable body. There are several models that are able model this type of deformable object including: dynamic splines method,^{24,27,28} mass-spring model,^{17,25} Cosserat theory,^{1,2,26} rigid bar with joints^{18–20} and FEM using the beam element.^{16,23,29,30} Limitations of different models are summarized into following aspects: (1) Dynamic splines methods are widely used to model complex contact configurations; this approach does not model material torsion. Furthermore, dynamic splines method is a geometrically-based model (non-physically-based model). This method is commonly employed to computer-based animation less accuracy required. It is not suitable to model the kinetic behavior of the colonoscope precisely. (2) Cosserat theory takes into account all possible deformations of a one-dimensional object. The main drawback is how the contact force of the scope from the colon is handled.¹⁶ This remains a critical issue using Cosserat theory. (3) Mass-spring model is a simplest and most intuitive model. Discrete point masses (particle system) connected together by a network of mass-less spring. This method has been used to model skin, fat, muscle, cloth and so on for computer animation. But it is not an enough accurate model because it is not built upon elasticity theory. In practice, spring constants k_s of mass-spring model are often chosen arbitrarily, and one can say little quantitatively about the material being modeled. (4) The model of rigid bars

connected by joints has been applied to the computer-based endoscopy simulator despite unrealistic animation of simulators compared to the real dynamic behavior of the scope such as the loop formation in colonoscopy. Furthermore, the nature of the colonoscope is not rigid bar connecting with joints. (5) FEM is the closest to describe the physics of an elastic material since they are based in the strong mathematical foundation of continuum mechanics. Beam theory provides a solid foundation to model a long deformable object by FEM, where a physics-based model consists of a set of connected beam elements that can model bending, twist and other deformations while allowing solid and hollow object of various cross-sectional geometries and mechanical properties to be modeled.

The colonoscope is defined as a set of beam elements. Each element has 3 degrees of freedom (DOF) in translation and 3 DOF in rotation. The force-motion of the colonoscope can be represented by dynamic equilibrium equation. The governing dynamic matrix is showed as Eq. (1):

$$[M]\{\ddot{U}\} + [D]\{\dot{U}\} + [K]\{U\} = \{F\} \quad (1)$$

$[M]$ is consistent mass matrix; $[D]$ is damping matrix, the most effective way to treat damping is to treat the damping value as an equivalent Rayleigh Damping in form of $[D] = \alpha[M] + \beta[K]$, in which $[D]$ = damping matrix of the physical system; $[M]$ mass matrix the physical systems; $[K]$ = stiffness matrix of the system; α, β are estimated by experimental data. $[K]$ is band matrix due to the serial structure of the model (one node is only shared by one or two elements). By overlaying each stiffness matrix, k_e representing an individual beam, the entire matrix $[K]$ for the colonoscope can be assembled. As each colonoscope beam elements bends the co-ordinate system for each element stiffness matrix must be transformed from the original co-ordinate system to an updated global co-ordinate system. A transformation matrix Λ is then defined to change the local frame of reference to a global coordinate system. This lead to the following relationship between k_e in the local coordinates and $\bar{k}_e$ in a global frame: $\bar{k}_e = \Lambda^T k_e \Lambda$. The flexural rigidity EI of the colonoscope has been tested and can be found in the references.^{8,15,16} $[U]$ = represents a column matrix of displacements corresponding to force vector $\{F\}$ (including external force F_e and contact force F_c). Contact force computation is formulated into LCP by linearizing Signorini's problem that is adapted into non-interpenetration with unilateral constraints. Frictional force is computed by the mechanical compliance of FEM models with consideration of dynamic friction between the scope and intestinal wall. The colon is modeled based on Timoshenko's beam theory, the stiffness matrix of colon model K_c is computed in terms of a hollow cylinder beam with length, thickness, and radius.

Contact Force Between the Scope and Intestinal Wall

Contact force computation with friction is a complex and important problem in the field of medical device simulation. Thus, contact modeling has attracted significant attention with a large number of formulations produced. A comprehensive literature review on this subject can be found in Gilardi *et al.*¹⁴ In general, three categories of formulations can be distinguished: the classical rigid body contact formulations, complementarity formulations and compliant contact formulations. Complementarity formulations are typically adapted into non-interpenetration with unilateral constraints. Contact force computation is formulated as a LCP by linearizing Signorini's problem.

Contact force F_c is computed by the mechanical compliance of FEM models using Eq. (2):

$$\begin{cases} f_n \geq 0 \\ \delta_n = [W]f_n + \delta_n^f \geq 0 \\ f_n \perp \delta_n \end{cases} \quad (2)$$

δ_n is the contact space; f_n is contact force; The matrix $[W]$ is Delassus operator; δ_n^f is free motion corresponding contact space.⁶

Each contact point of the colonoscope with the colon has a friction state, either a static or dynamic friction state. That is, when the colonoscope and the colon come into contact, there are generally two states in the tangential contact, stick and slip states. The relative displacement of the contact points of two bodies is equal to zero for the stick state, i.e., both ends of contact point of colonoscope and the colon move together. The slip state follows the stick state if tangential force is greater than the limit of the static friction force that is defined as the multiplication of frictional coefficient and the normal force. During the slip state, relative slip between the colonoscope and the colon along the tangential direction occurs. The friction force is determined by the multiplication of the frictional coefficient and the normal force. Consider a contact α on the node i of the colonoscope (with one constraint along the contact normal n and two along the tangential friction direction t, s). H_α is matrix of the frame $[n, t, s]$. The mechanical coupling of this contact with a contact β (with frame H_β) on the node j can be evaluated with the following 3×3 matrix, LCP with friction force based on Coulomb's friction law can be solved by a Gauss–Seidel (GS) like algorithm as Eq. (3) is shown.^{10–12,21}

$$\begin{cases} \delta_\beta - [W_{aa}]f_\alpha = \sum_{\beta}^{\alpha-1} [W_{\alpha\beta}]f_\beta + \sum_{\beta=\alpha+1}^m [W_{\alpha\beta}]f_\beta + \delta_\alpha^f \\ [W_{\alpha\beta}] = H_\alpha^T \left(\frac{M}{h^2} + \frac{D}{h} + K_s + K_c \right)_{(i,j)}^{-1} H_\beta \end{cases} \quad (3)$$

Where t is time step; M is the mass matrix, D is the damping matrix, K_s is the stiffness matrix for FEM model of the colonoscope; K_c is the stiffness matrix of the colon (the colon is modeled based on Timoshenko's beam theory, the stiffness matrix of colon model K_c is computed in terms of a hollow cylinder beam with length, thickness, and radius). δ_α^f is free motion corresponds essentially to the deformation of the beam elements under gravity and external manipulation (except contact force F_c) based on Eq. (1). Once the free motion δ_α^f is computed, contact force with friction f_α between the scope and intestinal tissue is determined in terms of two different frictional states.

Experimental Setup and Data Collection

Experimental setup consists of colon tray (Medical Innovations International Inc.) and porcine colon tissue (Medical Innovations International Inc.), the flexible force sensor (Tekscan Inc. Boston, MA), Ascension Trakstar-2 6 DOF sensors (Ascension Technologies Corp. Burlington, VT), Colonoscopy Force Monitor (abbreviation: CFM in this paper, Artann Laboratories, Trenton, NJ) and Olympus CF-Q160L colonoscope (Olympus Corp., Tokyo, Japan).

1. A porcine colon tissue is laid in human configuration on a special board developed specifically for this model: the “colon tray”. Specific regions of the colon are tacked down with a mesh material to represent the immobile intraabdominal attachment areas of the colon (Fig. 1).

2. CFM (Artann Laboratories, Trenton, NJ) is a hand-held wireless colonoscope attachment that continually measures, displays and stores the push/pull, clockwise and counter-clockwise torque applied to the insertion tube of the colonoscope²² (Fig. 2). The CFM system consists of 2 components: (1) handheld wireless colonoscope attachment with force-and torque-measuring ability (F and T) and (2) computer. CFM is connected to a computer. Force and torque readings are logged at a sampling rate of 30 Hz.
3. The flexible force sensor is a paper-thin (0.008") Flexiforce B201 sensors (Tekscan Inc. Boston, MA). The system has a handle that connects the force sensor. The plastic ELFTM (Economical Load and Force) handle contains data acquisition electronics with USB connection and interface to B201 sensors (Fig. 3). The flexible force sensor is applied to the colonoscope insertion tube to collect the normal contact force between the scope and the colon tissue. The flexible force sensor is calibrated to preload 4 N, 6 N, 8 N, 15 N force and adjusted the proper sensitivity. The plastic ELFTM handle is connected to a computer. The normal force readings are logged at a sampling rate of 30 Hz.
4. Position sensors and Colonoscope: an adult colonoscope CF-Q160L (Olympus Corp., Tokyo, Japan) is equipped with two electromagnetic Ascension Trakstar-2 6-DOF position sensors (Fig. 3) (Model-90 sensors from Ascension Technologies Corp. (ATC), Burlington, VT). Two sensors are placed at 0 cm, 25 cm from the distal end. Sensor 1 is placed to record the displacement and angulations of the distal end of the scope in 6-DoFs. The position of sensor 2 such that this sensor is approximately in the sigmoid colon when the distal end of the scope is in the descending colon or transverse colon region. Sensor 3 that is attached on CFM is to position the point of input exerted by CFM. The Sensor 4 is sutured on the surface of sigmoid colon that determines the motion of one segment in sigmoid colon on real-time, i.e., alternatively detect deformation of scope in sigmoid colon where the loop forms. Flat-plate transmitter is placed at 40 cm below the colon tray model. The original of coordinate frame is right underneath the joint between sigmoid colon and rectum colon on the colon tray. The ATC electromagnetic system is connected to an Intel 3.0 GHz computer with 4 GB RAM. The position readings are logged at a sampling rate of 30 Hz.

The procedure is performed using standard techniques including lubricating the insertion tube and insufflating air into the colon so that interactive condition of *ex vivo* tissue colonoscopy simulates colonoscopy performed on a human. Data collection is time-stamped and the three data stream is logged at 30 Hz with the same computer. Five replicate colonoscopies on each pig colon sample and three different sets of colon tissue were used. During the colonoscopy, external pull and push force and clock-wise and counter clock-wise torque (input of the model) are recorded by CFM (Fig. 4).

Rayleigh Coefficient Estimation

Data collected from several regions where the scope is advanced by pushing force and contact force between the scope and the colon, such as in sigmoid colon, descending colon, transverse colon, ascending colon were selected for data analysis. In the rectum, the scope is advanced without colliding force from the colon wall so that data collected from the rectum region was used for the damping estimation. The rationale for this approach is as follows: (1) single DOF from input and output is involved, in this case, the system identification become simple compared to multiple DOF from input and output that could induce more error to parameters we will identify. When the scope is advanced in the rectum, there is only one DOF of translational motion regarding X-axis involved. (2) Avoiding the same group of

data that is used for parameters estimation overlapped for verification of the model. In this section, the damping factors are estimated by using the experimental data.

$$\alpha[M]\{\dot{U}\} + \beta[K]\{\dot{U}\} = \{F\} - [M]\{\ddot{U}\} - [K]\{U\} \quad (4)$$

Clearly, this equation is linear model. In order to estimating two coefficients values of α , β , the least square method is used. For the linear model:

$$y = f(X, \beta_1, \beta_2) + \varepsilon = \beta_1 x_1 + \beta_2 x_2 + \varepsilon \quad (5)$$

We know the sum of squared errors $S(\beta_1, \beta_2) = \sum_1^n [Y_i - (\beta_1 x_1 + \beta_2 x_2)]^2$, in order to simplify format of $S(\beta_1, \beta_2)$, we have the matrix format that is

$$S(\beta) = (Y - X\beta)^T (Y - X\beta) \quad (6)$$

where:

$$Y = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} \quad X = \begin{pmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \\ \vdots & \vdots \\ x_{n1} & x_{n2} \end{pmatrix} \quad \beta = \begin{pmatrix} \beta_1 \\ \beta_2 \end{pmatrix}$$

Take derivative of Eq. (6), we have:

$$\frac{\delta S(\beta)}{\delta \beta} = \frac{\delta (Y - X\beta)^T (Y - X\beta)}{\delta \beta} = -2X^T Y + 2X^T X\beta \quad (7)$$

In order to obtain the least square estimation parameters β_1 and β_2 , let Eq. (7) $\frac{\delta S(\beta)}{\delta \beta} = 0$, we can have two parameters β_1 and β_2 :

$$\beta_{LS} = [X^T X]^{-1} X^T Y \quad (8)$$

Eq. (8) is the solution of estimating two parameters β_1 and β_2 .

Alpha and Beta's values of Eq. (8) are estimated in term of experiment data: alpha = 0.34 and beta = 0.0177.

Porcine Colon Tension Test

In order to determine the strength of the porcine colon that was used for colonoscopy simulation we implemented the swine colon by tension test. In this study, samples from different parts of the porcine colon are prepared and tested. The elongation of the colon is up to 120% of the original length, and we should consider the reduced area for each load and transform the engineering stress–stress curve in a true stress–strain curve. The engineering stress and strain is converted into true stress and strain. Figure 5 shows both engineering and true stress–strain curves of pig colon. For small strains, engineering and true stress–strain curves have relatively similar values, but there are significant differences of stress as the

strain goes to large values because of the reduction of area. The mechanical property of the colon tissue is a quasilinear viscoelastic model,^{8,9,13} but in this research it is assumed to linear model from a load value of 0–20 N ranges when contact force is not go beyond too much during a colonoscopy.

RESULTS

During a colonoscopy on porcine colon model, the scope is subjected to dynamic (time-dependent) force/torque, i.e., primary pushing force/torque is a time-varying load during a complete colonoscopy, the displacements induced will be also vary with respect to time. A typical load for the colonoscope during one interval should be selected to apply the model for simulation. We have introduced the location of four sensors where these sensors are positioned. These sensors not only record the displacements of the scope but also read the node's coordinates of finite beam elements for the instrument in three dimension (x, y, z), which determines the geometry of the scope and the colon. Sensor 1 records the coordinate of the distal end of the scope. Sensor 2 is approximately in the sigmoid colon when the distal end of the scope is in the descending colon or traverse colon region. Sensor 3 that is attached on CFM is to position the point of input exerted by CFM. Sensor 4 is sutured on the surface of sigmoid colon that determines the motion of one segment in sigmoid colon on real-time, i.e., alternatively detect scope's shape in sigmoid colon where loop forms. The original of coordinate frame is right underneath the joint between sigmoid colon and rectum colon on the colon tray, which is fixed during the whole procedure. Material property, constraints, a time-varying contact force and external loads are applied to the FEM model of the scope. A time step is determined by the sampling rate 30 Hz of data collection during the experiment.

When the scope was in the descending colon, the distal end of the scope has two active DOF displacements along x-axis and z-axis (displacements along Y-axis are constrained because of the immobile intraabdominal attachment areas for the descending colon), and has no significant rotation angles change. Simulation results from displacement of the scope along x-axis and elevation angle of the scope about Y-axis are compared to experimental data as Figs. 6 and 7 show respectively. Root mean square error (RMSE) of displacement of the scope along x-axis in the descending colon is 1.597 mm and coefficient of variation (CV) %_{RMS} = 18.43%. RMSE of elevation angle of the scope about Y-axis in the descending colon is 0.1561 degrees and the (CV)%_{RMS} = 18.9%.

When the scope was in the ascending colon, simulation results from displacement of the scope along x-axis are compared to experimental data as Fig. 8. RMSE of displacement of the scope along x-axis in the ascending colon is 0.9606 mm and the (CV)%_{RMS} = 14.93%.

During colonoscopy test, contact pressure between the scope and the colon is recorded by the contact force sensor. Contact pressure comparison between the simulation results and recorded data by the contact force sensor for the distal end of the scope on the colon wall is showed as Fig. 10 when the scope was in the descending colon. RMSE of the contact force of the distal end of the scope in the descending colon is 0.0752 N and the (CV)%_{RMS} = 17.68%.

DISCUSSION

According to Figs. 6, 7, 8, and 9, the experimental data has a satisfactory agreement with the value calculated from the mathematical model. In general, simulation results show more displacements than experimental data when the scope was in the ascending colon. There is a potential reason that should be pointed out. The sigmoid colon could deform (elongation) while the scope is advanced step by step during this time interval. Therefore, the retraction

force from deformation of the sigmoid colon could act on the scope, which in fact could be additional frictional force acting on scope when the scope is pushed forward next. In reality, endoscopists feel pulling force back during the loop formation in sigmoid colon, which comes from deformation of the colon while the scope is held. This retraction force should be accounted as a kind of frictional force during next advance of the scope. Based on this reason, ideally the scope without such retraction force would advance more than it does, therefore simulation results shows more displacements of the distal and proximal end of the scope while there was a loop formation in sigmoid colon.

In fact, Measurement uncertainty error is not inevitable during data collection either Model-90 position sensors or the force sensor (CFM and the flexible force sensor). The measurement error of position sensors come from jittery data i.e., there exist the data jittery and somewhat discrepancy whenever position sensors are placed on stationary objects or moving objects, which should be included as one of error factors. The measurement error is plotted as error bar showed in all figures. For the model simulation results, we also need to consider a potential propagation error generated from CFM, where the CFM collected the external force/torque is applied to the simulation of the kinetic model. Besides the propagation error for the simulation results, there also was an assumption for the linear relationship of stress–strain for the colon tissue. In fact, the non-linear mechanical property of colon tissue is shown in Fig. 5 through the colon tensile test.

Cheng *et al.*⁶ found that the scope's location and the loop of scope affect on flexural rigidity EI of the scope so that the mathematical model with different flexural rigidity EI value of the colonoscope should be tested to see if the flexural rigidity EI result in error for simulation results. We test three different flexural rigidity EI values of 300, 400, 700 Ncm² to see if there is a difference from the distal end of the scope.

We compared these displacement computed by using three different flexural rigidity EI values to experimental data in Fig. 10. The flexural rigidity of the colonoscope effects was assessed by investigating the difference among different EI using ANOVA with the *p* value of 0.58, which indicate that there is no significant difference among these data using three different flexural rigidity of the colonoscope. Thus, we concluded that location and the loop of the scope effect on flexural rigidity EI of the scope can be neglected in this research. In future work, we will test the reliability of the mathematical model by using the different model of the colonoscope and geometric model of the colon.

CONCLUSION

In this paper, the kinetic model of the scope is developed and validated by the porcine colon colonoscopy. The experimental data has a satisfactory agreement with the value calculated from the kinetic model in general. The model is able to predict the kinetic behavior of the scope, and provides the information such as the shape of the scope, direction of the colon, forces exerted with certain sections. It is expected that with the help of this model, the surgeon may be able to adjust the operation to avoid the loop formation and perforation of the colon.

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ABBREVIATIONS

CFM	Colonoscopy Force Monitor
FEM	Finite Element Method
LCP	Linear Complementarity Problem
ELF	Economical Load and Force
ATC	Ascension Technologies Corp
DOF	Degree of Freedom
RMSE	Root mean square error
CV	Coefficient of variation
ANOVA	Analysis of variance

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FIGURE 1.
A porcine colon tissue in the colon tray.

FIGURE 2.

A colonoscope is equipped with three different sensors.

FIGURE 3.
Primary pushing and pulling force during a complete colonoscopy.

FIGURE 4.
Primary synchronized data regarding input force and output motion.

FIGURE 5.
True and engineering stress-strain curves in tension of the swine colon.

FIGURE 6.
Displacement of the distal end of the scope along x-axis in the descending colon.

FIGURE 7.
Elevation angle of the distal end of the scope about y-axis in the descending colon.

FIGURE 8.
Displacement of distal end of the scope along x-axis in ascending colon.

FIGURE 9.
Contact pressure between the distal end of the scope and the colon wall in the descending colon.

FIGURE 10.

Displacement of distal end of the scope comparison between simulation results with three different flexural rigidity EI values and experimental data along x-axis in the descending colon.