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ORIGINAL ARTICLE

Evaluation of flexible endoscope steering using haptic guidance

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Abstract

Background Steering the tip of a flexible endoscope relies on the physician's dexterity and experience. For complex flexible endoscopes, conventional controls may be inadequate.

Methods A steering method based on a multi-degree-of-freedom haptic device is presented. Haptic cues are generated based on the endoscopic images. The method is compared against steering using the same haptic device without haptic cues, and against conventional steering. Human-subject studies were conducted in which 12 students and 6 expert gastroenterologists participated.

Results Experts are significantly faster when using the conventional method compared with using the haptic device, either with or without haptic cues. However, it is expected that the performance of the subjects with the haptic device will increase with experience.

Conclusions Using a haptic device may be a viable alternative to the conventional method for the control of complex flexible endoscopes. The results suggest that the use of haptic cues may reduce the patient discomfort.
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Keywords Colonoscopy; endoscope steering; haptic guidance; image-guided surgery; medical robotics

Introduction

Flexible endoscopy is a minimally invasive procedure that aims to inspect the internal body cavities via the natural body openings. A common endoscopic procedure is colonoscopy, the inspection of the colon via the rectum. The physician uses a flexible endoscope which is steered through the body by controlling the orientation of the endoscope tip, while manually feeding the endoscope into the patient. The tip orientation is controlled using two wheels that are positioned on the control handle (Figure 1). The endoscopic images are displayed on a monitor.

During a colonoscopy, the endoscope is first introduced up to the cecum, which is at the end of the colon, and then the visual inspection is performed while the endoscope is slowly retracted. In order to maneuver the endoscope through the colon, and to ensure appropriate investigation and visualization, the physician needs to steer the tip accurately.

Usually, the physician uses one hand to operate the wheels that control the tip, while the other hand is used to feed the endoscope into the patient (1). However, it is sometimes necessary for the physician to use

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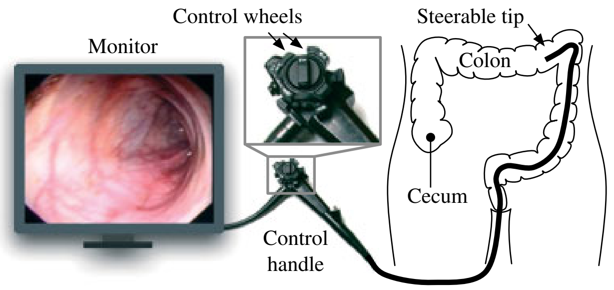

Figure 1. Conventional colonoscopy: the physician uses the control wheels to control the steerable tip while feeding the endoscope into the patient up to the cecum. The endoscopic images are observed on the monitor

both his/her hands in order to manipulate the wheels accurately. Since control of the tip requires spatial reasoning and dexterity, the introduction of the endoscope may take significant time and effort. The control of the tip orientation is also not very intuitive, as the two directions (up/down and left/right) are controlled by two concentric wheels. Therefore, experience is necessary to master this procedure (2). This makes endoscope steering difficult, especially for less experienced physicians.

Despite the fact that current endoscopes are difficult to steer, complex endoscopes are currently being developed, which require significantly more effort to control. These include the EndoSAMURAI (Olympus Corp., Tokyo, Japan) and the ANUBIS (Karl Storz GmbH & Co. KG, Tuttlingen, Germany). These endoscopes feature sophisticated instruments, to be used for Natural Orifice Transluminal Endoscopic Surgery (NOTES). These endoscopes can no longer be controlled by one physician. Controlling the endoscope by multiple physicians is undesirable because of the costs and the fact that this requires optimal cooperation between the physicians. A solution would be to use a multi-degree-of-freedom (DOF) steering device enabling control of all instrument motions by one physician.

Allemann *et al*. have developed a system in which they use a joystick to control a flexible endoscope (3). In their evaluation, both novices and experienced physicians required significantly more time to complete a given task when using a joystick compared with conventional controls. However, in their experiment, rate control was applied whereas position control might be more appropriate for this task. According to Zhai (4), rate control is suitable when the workspace is large, while position control is more suitable when accurate manipulation in a limited workspace is required. The latter is the case for endoscope steering. Furthermore, the design of the setup limited the rotation of the endoscope around its axis.

Steering using haptic guidance

In this research study, we developed a control method designed to assist the physician in his/her steering task, and evaluated its effectiveness. Our approach is to let the physician control the endoscope tip via a multi-DOF haptic device. This allows for intuitive coupling between the motion of the input device and the endoscope tip, while enabling the use of haptic guidance to steer the physician in a certain direction.

By using a multi-DOF haptic device, the control can be designed such that the movement of the endoscope tip matches the movement of the physician's hand. This will result in intuitive steering. Additionally, the haptic device can be held in one hand, as opposed to the conventional control handle which may require both hands to operate. Single-handed steering allows the physician to use his other hand to feed the endoscope into the patient without the use of an assistant, improving the quality of the endoscopy (1).

In addition to making the endoscope control intuitive, haptic cues may also be given to the physician. Haptic cues can be used to improve the physician's performance (5,6). They play an important role in the training of physicians using medical simulators (7). Using haptic guidance, we aim to help the physician to steer the endoscope tip in the appropriate direction, i.e. in the direction of the lumen. Implementing haptic guidance can increase the performance of the physician, and reduce the cognitive load. This increases the cognitive reserve available for inspection of the endoscopic images for abnormalities (8).

In order to apply the haptic guidance, the direction of the lumen needs to be determined. Using a purely mechanics-based approach to calculate the lumen direction would require an accurate model of the endoscope as it interacts with the soft tissue. Since the *in vivo* tissue parameters are unknown, such an approach is realistically not possible. Therefore, we will use the endoscopic images to determine the direction of the lumen.

An overview of endoscopic image processing algorithms is given by Liedlgruber (9). However, these algorithms were not designed for use in the feedback of a control loop. As such, their performance in terms of robustness and processing speed may not be sufficient. Therefore, we use an algorithm based on our previous work (10). This algorithm finds the dark region of the endoscopic image, which is the part that is furthest away from the camera. This is the center of the lumen.

Evaluation

The endoscope steering system was evaluated using a flexible endoscopy simulator. Human-subject studies were performed in which 18 subjects, 6 experienced gastroenterologists and 12 students, performed a simulated colonoscopy. Every subject used three different control methods: a haptic device with haptic guidance, the same haptic device without haptic guidance, and a conventional endoscope. Their performance was evaluated on introduction time, patient discomfort and percentage of the colon that was visualized.

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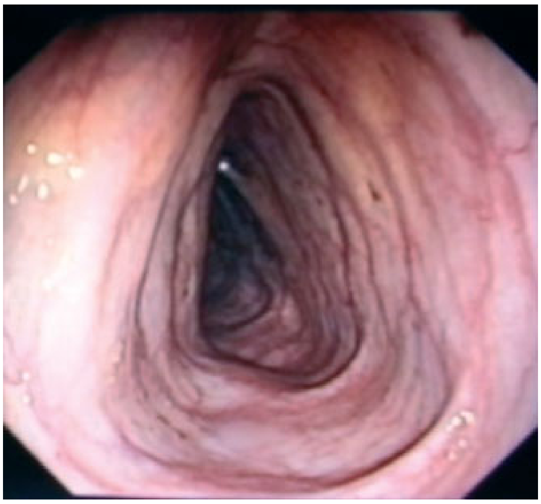

Figure 2. Endoscopic image within the colon: the physician tries to keep the lumen centered in the image while introducing the endoscope

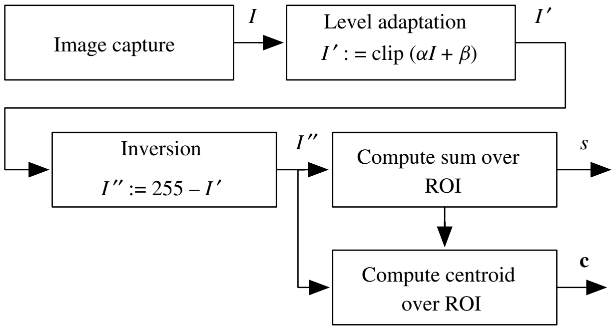

Figure 3. From the input image that is captured (*I*), the levels are adapted resulting in image *I*'. This image is then inverted yielding *I*″. From *I*″, the sum *s* and centroid c are computed

Outline

This paper is structured as follows: in the following section the endoscope control method using haptic guidance is discussed and the experiment designed to evaluate this control method is described. Then, the results of this experiment are given, and the final section concludes and provides possible directions for future work.

Materials and Methods

Endoscope control using haptic guidance

During the introduction phase of colonoscopy, the physician generally tries to steer the endoscopic camera in the direction of the lumen. In this situation, the lumen is centered in the image, as shown in Figure 2. This ensures that the endoscopic camera stays clear of the colon wall. In order to assist the physician in this steering task a force is applied to the haptic device in the direction that is required to center the lumen. The algorithms used to determine the center of the lumen, and to provide haptic guidance, are described in the following subsections.

Lumen center detection

In order to determine the preferred direction of the endoscope, the endoscopic images are used to find the direction of the lumen. Possible approaches are optical flow-based methods and image intensity-based methods.

In an optical flow-based approach, subsequent images are used to determine the motion of the environment as perceived by the camera (11). This approach has been used successfully to steer mobile robots away from obstacles and through corridors (12,13), a task which is similar to steering the endoscope through an endoluminal path. In previous work, we used such an approach successfully in a simulated environment that modeled the view of a camera moving through a rigid model of the colon (10). However, we found that in reality, robustness suffers from motion blur caused by sudden motions that occur when the endoscope is introduced manually.

In an image intensity-based approach, a single image is used to find the direction of the lumen. Owing to the arrangement of the camera and the light source in the endoscope tip, areas that are further away from the camera appear darker in the image (Figure 2). This approach has been used successfully for the purpose of lumen contour detection (14,15) and polyp detection (16,17). In this present research, adaptive thresholding is used to obtain a binary image, which is then processed to obtain the shape of the lumen wall. However, for the purpose of finding the appropriate haptic guidance, we are not interested in an accurate description of the lumen wall shape, but more in a robust estimation of the lumen center. Moreover, the algorithm should run in real time at the speed of the vision system (25 frames per second). In order to meet these requirements, we have developed an algorithm that uses the centroid of the dark area of the image (10).

The block diagram of the algorithm is shown in Figure 3. A color image is captured, which is converted to a grayscale image $I(x, y)$, where x and y indicate the horizontal and vertical pixel positions, respectively. $x = 0$, $y = 0$ represents the center of the endoscopic view. $I(x, y)$ is an 8 bit image, with 0 and 255 representing black and white, respectively. An example input image is shown in Figure 4(a).

In order to extract the dark area of the image, first the intensity levels are adapted to increase the contrast. The new image $I'(x, y)$ is computed by

$$I'(x, y) := \text{clip}(\alpha I(x, y) + \beta)$$

where clip() denotes limiting the values to the range 0–255. Parameters α and β influence the contrast and the intensity levels of $I'(x, y)$, respectively. When the algorithm is used in a simulated environment, parameters α and β can be constant values, since the illumination will

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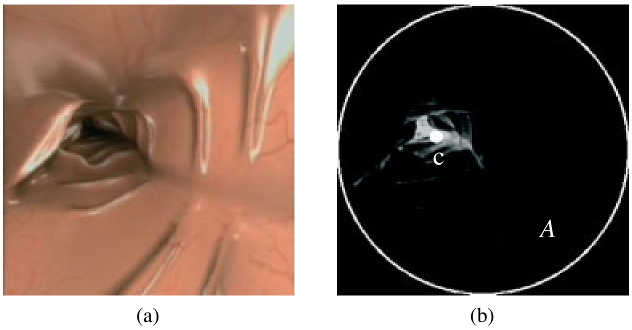

Figure 4. Lumen center detection: (a) example image from the endoscopy simulator that is provided as input to the algorithm. (b) Image (a) with the levels adapted and inverted. The ROI *A* and the centroid c are marked

be constant. For the experiments, $\alpha = 16$ and $\beta = 0$ were used. In order to use the algorithm in a real environment, it may be necessary to automatically adapt α and β when changes in illumination occur. An algorithm that performs such an adaptation was presented in (10).

The image $I'(x, y)$ with increased contrast is inverted:

$$I''(x, y) := 255 - I'(x, y)$$

The inverted image $I''(x, y)$ (Figure 4(b)) clearly shows the direction of the lumen. In this image, a circular region of interest (ROI) A is defined, as shown in the figure. A circular ROI is used, because the corners of the image often contain dark regions due to the lighting of the endoscope. These regions would adversely effect the algorithm, Over the ROI, sum s and centroid $\mathbf{c}$ of the resulting inverted image $I''(x, y)$ are computed as:

$$s := \sum_{(x,y)\in A} I''(x, y),$$

$$\mathbf{c} := \frac{\sum_{(x,y)\in A} \begin{bmatrix} x \\ y \end{bmatrix} I''(x, y)}{s}.$$

We define the resulting centroid $\mathbf{c}$ as the direction of the lumen. The sum s will be used to determine whether the direction of the lumen could be found. When s is small, this means that the dark region is small, and the direction $\mathbf{c}$ that was found is likely to be inaccurate. If s is smaller than a given threshold, it is assumed that the direction could not be found. This situation occurs at 'bends' in the colon, the sigmoid colon, the hepatic flexure, and the splenic flexure, as shown in Figure 5. In these cases, no haptic guidance will be given, since the direction of the lumen cannot be determined reliably. Enabling and disabling the haptic guidance is done using a smooth transition in order not to present sudden changes of force to the user.

Haptic guidance based on lumen position

The image-processing algorithm described in the previous section computes the lumen position $\mathbf{c}$. This direction is

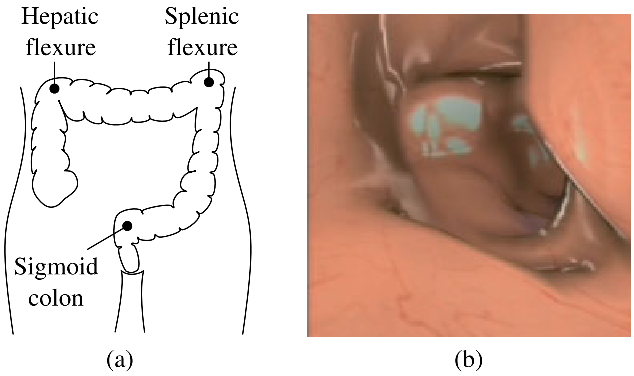

Figure 5. Areas where the lumen cannot be found: (a) this situation occurs in the hepatic flexure, the splenic flexure, and the sigmoid colon. (b) Example image of this situation in the hepatic flexure

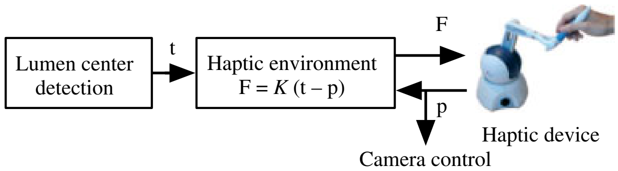

Figure 6. The target t is computed by the lumen center detection. This is used as the equilibrium point for a linear spring model with stiffness *K*. The spring model is used to compute the force F for a given position p of the haptic device

used to display a haptic environment to the subject. The 2D lumen position $\mathbf{c}$ is mapped to 3D target point $\mathbf{t}$ on a vertical plane. We have implemented a linear spring model that will pull the user in the direction of the target $\mathbf{t}$, given by

$$\mathbf{F} = K(\mathbf{t} - \mathbf{p})$$

where $\mathbf{F}$ is the applied force, $\mathbf{p}$ is the position of the haptic device and K is the stiffness. This is illustrated in Figure 6. Position $\mathbf{p}$ is used to steer the endoscopic camera.

The haptics loop is computed at an update rate of 1000 Hz. The parameters are updated by the image-processing algorithm at the frame rate of 25 frames per second. We evaluated this steering method in a human-subject experimental study.

Experimental conditions

In order to assess the value of endoscope steering using haptic guidance, we compared it with two other endoscope steering methods. These methods are *conventional steering* and *steering without haptics*.

Conventional steering

The *conventional steering* method allows the subject to control the endoscope tip using the endoscope control wheels. This method of steering is the current practice in flexible endoscopy. However, this method of steering is not very intuitive, which makes the control hard to learn

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(2). We will use this method as a reference to compare the other steering methods.

Steering without haptics

The *steering without haptics* experimental condition uses the same haptic interface that is used to evaluate *steering with haptics*, but does not provide the haptic feedback. This method is included to evaluate whether differences between *conventional steering* and *steering with haptics* are caused by the use of haptics, or by the difference in the interface.

Steering with haptics

The experimental condition *steering with haptics* is the steering method already described. Haptic guidance is provided to the subject, based on the endoscopic images.

Survey

In order to determine an appropriate model to perform flexible endoscopy, we conducted a survey among five gastroenterologists. Four of them were also part of our expert subject group of the experiment. We asked them to give their opinion on the anatomical model, the flexible endoscopy simulator, and the animal model. These are three models that are commonly used for flexible endoscopy training. We also asked them which criteria should be used to assess how well someone performs a flexible endoscopy.

Two out of the five gastroenterologists had used an anatomical model. They indicated that the ‘feel’ of the model is better than interacting with a computer simulation, although it is different from a real patient. On the other hand, they found the images less realistic than a computer simulation. All gastroenterologists had used a flexible endoscopy simulator. It was commonly described as being quite realistic. The subjects do not find the force-feedback that the simulator gives very realistic, but they consider this a minor limitation. Despite this limitation, they consider the simulator useful for the evaluation of basic steering skills.

Regarding the evaluation of the endoscopy, the consensus of the participants of the survey is that it is important to reach the target quickly, without too much discomfort for the patient. Subsequently, enough time should be spent to inspect the colon thoroughly during retraction.

During colonoscopy, reaching the cecum (the boundary between small bowel and colon) and the time required to do so are important criteria. During retraction, the entire colonic mucosa should be visualized properly.

Experimental methods

Based on the survey results, we selected the flexible endoscopy simulator as the model, since it is considered reasonably realistic and is easy to use (unlike animal models). Another advantage over other models is that it outputs several metrics that can be used to evaluate the performance. These include the total procedure time, the introduction time, the insertion depth, the patient discomfort, and the percentage of the mucosa that was visualized. The latter two are not available on any of the other models. Furthermore, using a simulator ensures that the test environment is identical for all subjects and for all experimental conditions.

We used the AccuTouch endoscopy simulator (Immersion Corp., San Jose, CA, USA). This simulator is used for training and evaluating gastroenterologists. Expert colonoscopists consider this simulator to be realistic (18). Furthermore, its validity has been demonstrated in several trials, summarized by Carter *et al*. (19). We used the ‘colonoscopy introduction case 1’, since it is the easiest case. An easy case was chosen to ensure all students could complete the case. The other simulator cases are of a more difficult level.

Evaluation criteria

Based on the survey results, three metrics that could be obtained from the simulator were chosen as criteria for the experiment. These were the introduction time, the patient discomfort, and the percentage of the colonic mucosa that was visualized (the visualization performance). The first two criteria are chosen since the gastroenterologists stated that during introduction, the target should be reached quickly without causing too much discomfort. The visualization performance was chosen since it shows how well the subject performs the inspection. Proper inspection was considered an important criterion by the participants of the survey.

The simulator does not give one single value for the discomfort of the patient, but a set of values that indicate how long the patient had mild, moderate, severe, and extreme discomfort. These represent the force levels exerted on the colon. We denote these values as d_1, d_2, d_3, and d_4, in increasing order of discomfort. In order to obtain one value for the discomfort, we use a linear combination:

$$D := \alpha_1 d_1 + \alpha_2 d_2 + \alpha_3 d_3 + \alpha_4 d_4$$

where D denotes the total discomfort value. Since each higher level of discomfort is much more severe, we have chosen to use an exponential set of parameters: $\alpha_1 = 1$, $\alpha_2 = 2$, $\alpha_3 = 4$, $\alpha_4 = 8$. Hence, 1 second of extreme discomfort (d_4) is equivalent to 8 seconds of mild discomfort (d_1).

Test setup

A test setup was built to enable evaluation of the three control methods. An overview of this setup is shown in

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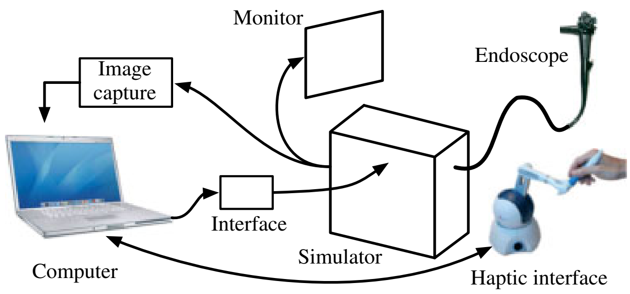

Figure 7. For the experiments, the simulator is not controlled by the endoscope controls, but by the control signals from the computer. The images of the simulated procedure are captured by the computer to be processed by the vision algorithm

Figure 8. The test setup in use by one of the gastroenterologists

Figure 7, and a picture of the setup in use is shown in Figure 8.

In order to control the simulator with the haptic device, an interface was developed. The simulator endoscope is not a functional endoscope, it is merely a device that reports the position of the control knobs to the simulator. An interface was built to emulate this, and to allow the computer to control the reported control knob positions. In this way the computer can control the simulation, based on the input from the haptic device. A Phantom Omni (SensAble Technologies, Inc., Woburn, MA, USA) was used as a haptic device.

The test setup also features an image capture device (ADVC55, GrassValley, Conflans St. Honorine, France), that allows the computer software to acquire the simulated endoscopic images. These are used by the image processing algorithm.

In all experimental conditions, the subjects still feed the endoscope manually into the simulator in order to move the endoscope forward through the colon. However, its controls are used only in experiments in which conventional steering is evaluated.

Tip control

Position control was implemented to steer the endoscope tip using the haptic device. The coupling between the haptic device motions and the camera motions was chosen so as to simulate the physician holding the camera in his/her hand. That is, left/right movements of the tip were coupled to horizontal camera motion, up/down movements were coupled to vertical camera motion. Subjects could control the camera rotation by rotating the endoscope itself using their right hand. This is identical to how the rotation is controlled in conventional endoscopies.

Motion towards and away from the haptic device was ignored. This motion was limited by a spring force towards a vertical plane. The orientation of the stylus of the haptic device was also ignored.

The proportional gain was chosen such that a displacement of 100 mm from the neutral position corresponded to maximum camera motion. This gain was chosen based on initial experiments. It allowed the full camera motion range to be covered, given the workspace of the haptic device.

Procedure

In order to be able to make a ‘repeated measures’ comparison, all subjects performed the three experimental conditions. The subjects were instructed to try to reach the cecum quickly with minimum patient discomfort, and to carefully inspect the colonic mucosa while retracting. They were instructed to use their left hand for steering the tip (using either the endoscope controls or the haptic device), and their right hand for feeding the endoscope. This configuration was chosen since it is identical to the way conventional endoscopic procedures are performed.

For each control method, they were given 15 min practice time, followed by the measurement session where the evaluation criteria were recorded. During the practice time, instructions were given on the use of the simulator and the control method. No instructions were given during the measurement session. All three experimental conditions were tested in succession without a break in between. This took approximately 1–1.5 hours per subject.

We counterbalanced the order of the measurements, i.e. each of the six possible orders of the three conditions was performed equally often. This was done in order to minimize the influence of any learning effects and fatigue on the evaluation in both subject groups.

Subjects

A total of 18 subjects were recruited for the experiment, 6 experienced gastroenterologists (this is the experts group) and 12 Technical Medicine[1] students. All experts had

[1] Technical Medicine is a Master’s level program at the University of Twente where students study to integrate advanced technologies within the medical sciences to improve patient care.

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performed over 1000 colonoscopies. All students had recently completed a flexible endoscopy course, in which they performed several colonoscopies using the same simulator that was used in the experiment.

None of the subjects had previous experience with similar experiments. The subjects participated on a voluntary basis, and signed an informed consent form. The subjects in the students group received financial compensation for their participation (€ 15).

During the experiment, two students caused a colon perforation during the introduction phase while using the *steering with haptics* method. This is a serious complication, which caused the simulator to abort the procedure. Hence, there are no results for these two subjects. In order to maintain a counterbalanced experiment design, two additional subjects participated to replace the original subjects. Of course, the fact that the two colon perforations took place, needs to be considered when comparing the three control methods.

It should be noted that perforations generally do not take place at the endoscope tip. Instead, they are caused by excessive looping of the endoscope in the sigmoid colon (Figure 9). Preventing looping is a major challenge in colonoscopy, and is learnt mainly by experience. By adequately retracting and/or rotating the endoscope during the procedure, looping can be minimized (1). When a loop is formed, it is very difficult to move the endoscope tip forward, and an inexperienced subject may use excessive force when trying to move the tip despite the loop, resulting in perforation.

The student subject group used for the analysis consisted of four females and eight males, aged 21–24 years, with an average age of 22 years. All were right-handed.

Within the experts group, there was one subject who did not succeed in reaching the cecum (the end of the colon) using the *steering without haptics* method. This subject was replaced with another expert subject. Here too, we need to take the fact that the original subject did not reach the cecum into account when evaluating the results.

The expert subjects that were used for the analysis were all male, aged 39–66 years, with an average age of 51 years. All were right-handed.

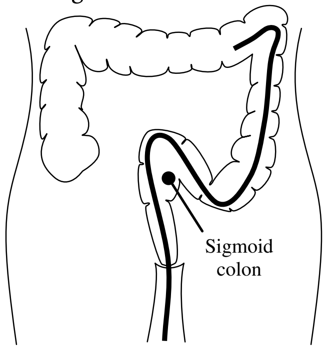

Figure 9. A loop formed in the sigmoid colon may cause perforation during introduction

Results

The results of the experimental study are shown in Figure 10. These graphs show the average introduction time, discomfort, and visualization for each of the three experimental conditions, for both the students and the experts.

Three two-way mixed analyses of variance (ANOVA) were performed for the whole group of subjects. These were done on the introduction time, the discomfort, and the visualization, with the control method (*conventional, without haptics, with haptics*) as a factor and expertise (student, expert) as a between-subjects factor. Only significant effects ($p < 0.05$) are reported.

The analysis showed a significant control method × expertise interaction ($F(2,32) = 4.971$, $p = 0.013$) for the introduction time. This means that the influence of the method on the introduction time is different for the two groups. As seen in Figure 10, students are on average slower when using the conventional method as compared with the other methods, while the experts are on average faster when using this method.

The analysis also showed a significant influence of the factor expertise on the introduction time ($F(1,16) = 14.172$, $p = 0.002$). As seen in Figure 10, the experts are on average faster than the students.

Furthermore, a significant influence of control method on patient discomfort was found ($F(2,32) = 3.586$, $p = 0.039$). Subsequent pairwise comparisons with Bonferroni corrections showed no significant results. As seen in Figure 10, this result probably indicates that the *without haptics* method causes most discomfort. In addition, three repeated measures ANOVAs were performed separately on the students and the experts groups. For the introduction time, a significant influence of the control method was found for the experts group ($F(2,10) = 8.378, p = 0.007$). Subsequent pairwise comparisons with Bonferroni corrections showed that conventional steering differed significantly from *without haptics* ($p = 0.042$) and from *with haptics* ($p = 0.013$). As seen in Figure 10, the experts are faster with the conventional method than with the other two methods.

Discussion

Within the experts group, the subjects performed significantly faster when using the conventional method compared with the other two methods. In addition, one of the original expert subjects did not succeed in reaching the cecum in the *without haptics* experimental condition. It is not remarkable that the experts perform better using the conventional method, since they have experience of over 1000 procedures using this method, versus experience of 15 min with the other two methods. Thus, their performance in the *without haptics* and *with haptics* conditions may improve with learning, possibly beyond their performance using the *conventional steering*.

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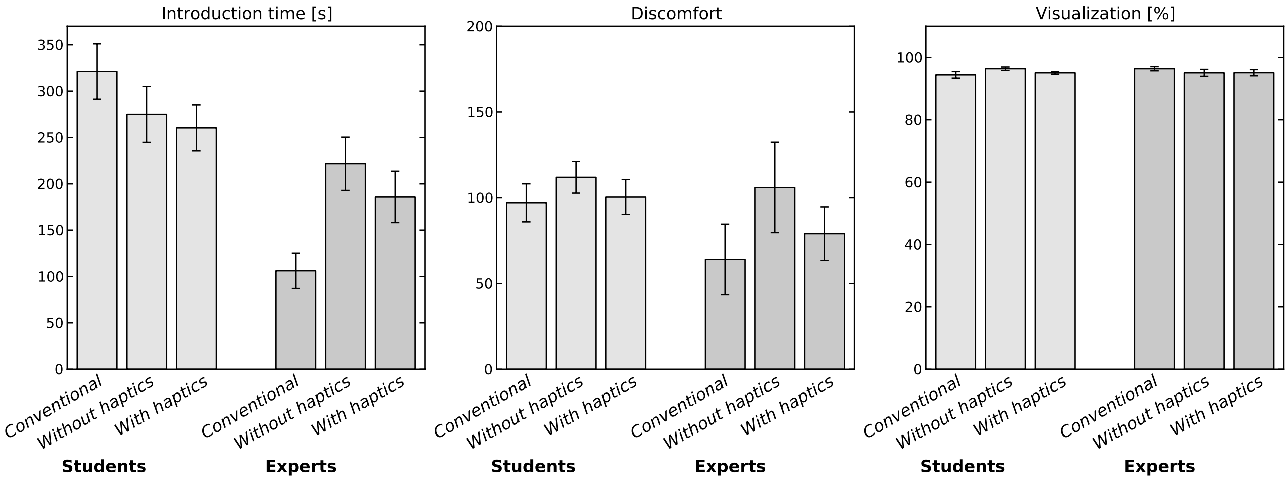

Figure 10. Results of the experimental study: the experts are significantly faster when using the *conventional* method compared with the other two methods. For the subject group as a whole, the *with haptics* method appears to result in less discomfort than the *without haptics* method. The error bars indicate the standard error

For the whole group of subjects, there was no significant influence of method on the introduction time. However, there was a significant influence on patient discomfort. The results suggest that *with haptics* the discomfort is reduced compared to *without haptics*. Thus, if a haptic device is used for endoscope steering, haptic cues may improve the performance.

For the students group, the results show no significant difference between the three methods. However, two students in the original subjects group caused colon perforation while using the *with haptics* method. They mentioned that they felt over-confident because of the haptic guidance. The risk of colonic perforation may be reduced by better training.

The results show some trends that are not statistically significant. It could be reasoned that adding more subjects to the experiment would increase the significance of the results. However, the number of available subjects is limited. The experiment requires 1–1.5 h per subject, and not many gastroenterologists have this amount of time available. The number of available student subjects is also limited, since we chose to select only students who had recently completed a flexible endoscopy course. Adding student subjects who had not recently completed this course would reduce the homogeneity of the group.

The results suggest that the 'new' steering methods that were implemented are better than steering using a joystick, as implemented by Allemann *et al.* (3). Their evaluation showed that both experienced and novice subjects required more time when using a joystick compared with using conventional control. In their study, endoscopists took almost 10 times longer, while surgeons and students required approximately twice as much time. In the present experiments, the experts required on average 43% more time, but students are on average 23% faster when using the *with haptics* method compared with *conventional steering* (although the latter result is not significant).

The results for the 'new' steering methods may be improved by using a different haptic device. The device that was used is a common off-the-shelf product, and was not designed specifically for the task. The results may have been affected in a negative sense because of the limited output force and the limited motion range. Furthermore, the mapping between the movement of the haptic device and the movement of the endoscopic camera can be optimized to improve the performance.

Conclusion

The results show that the experts are faster when using the *conventional steering* method compared with the 'new' steering methods. For the students, no significant differences were found. However, with new NOTES endoscopes, the conventional steering method will not be practical. The use of a multi-DOF input device may be a viable approach to controlling these endoscopes. The results suggest that in this case, implementation of haptic guidance may reduce patient discomfort. Since the performance of experts is likely to improve as they gain more experience, this control method may be a viable alternative to the conventional method.

Future work

Possible directions for future work include research on the learning curve of the 'new' control methods, improvement of the vision algorithm, and application of the 'new' control methods on NOTES endoscopes.

Experiments will be done in order to determine the learning curve of the three steering methods, i.e. to measure how the performance changes as subjects gain more experience. This allows prediction of the performance of an expert if he/she had used any of the 'new' steering methods from the beginning of his/her training. This will allow comparison of the steering methods without bias to the method that is current practice.

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The image processing algorithm can be improved, enabling it to find the direction of the lumen also in the areas where the current algorithm fails. This will guide the physician in these difficult areas, and possibly even perform the introduction automatically without the input of the physician. Furthermore, the system should give an indication to the user if the image processing algorithm is unable to find the lumen direction. The user can then be aware that he/she is no longer guided by the algorithm.

Future research will also be aimed at the control of NOTES endoscopes. It is likely that using a haptic device for endoscope control has the most benefits for these endoscopes since they are currently very difficult to control. If they could be easily controlled by a single physician, this would be a significant improvement over the current situation. NOTES endoscopes have two or more instruments with multiple degrees of freedom that emerge from the endoscope tip. The major challenge will be to control these instruments and the motion of the endoscope tip in an intuitive way.

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Conflict of interest

This is to certify that the authors have no financial or personal relationships with other people or organizations that would inappropriately influence our work.

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