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Design of a User Interface for Intuitive Colonoscope Control

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Abstract— **The goal of this study is to improve the efficiency and efficacy of the standard colonoscopy procedure. This is done by addressing the intuitiveness of colonoscope control. For this purpose an interface in the form of a grip was designed that allows the user to intuitively steer and drive the colonoscope. The Grip controls the orientation of the tip as if the colonoscope were a stiff instrument that pivots at the anus of a patient. To test the principle, experiments were conducted on a simulator operated by novice subjects. Initial experiments show a significant decrease in introduction time of 156 seconds ($p<0.005$). This technology will enhance current colonoscopy practice and open up possibilities for future applications of colonoscopy.**

I. Introduction

Colonoscopy is a medical procedure in which a colonoscope is used to visually inspect the large intestine (colon). A colonoscope is a flexible cylindrical shaft with steerable tip and a camera mounted on top. Wheels at the user end of the colonoscope, the control handle, make steering of the colonoscope tip possible (Fig. 1). The instrument is introduced into the colon through the anus of the patient in order to inspect the colon. Steering is done by operating the control handle that controls the tip and thus camera position of the colonoscope. A typical procedure takes about 20 minutes with current techniques. Colonoscopy is a common procedure which is recommended to all persons aged 50-75 to screen the bowel for cancer or premalignant tissue [1]. This procedure is primarily used for diagnostic purpose but can also serve for therapeutic interventions, e.g. removing premalignant lesions (polyps) or performing tissue biopsies (taking samples for further investigation). A polyp is abnormal tissue growth which has the potential to proliferate into cancer, usually colon and rectal cancer (CRC) [2]. Using colonoscopy for CRC screening is effective, but remains invasive and costly in time and effort because of the large patient population involved.

Gastroenterology literature suggests that a minimum of 100-500 procedures are necessary to accomplish competency in colonoscopy [3]–[6]. This long learning trajectory indicates the high levels of technical skills and understanding that are required to adequately steer the colonoscope. Firstly, anatomical parameters such as high compliance and fragility of the bowel wall and the suspension of the colon in the abdomen make introducing a colonoscope into the caecum (the end of the colon) a complex task [7], [8]. Secondly, the device is difficult to control: two rotations about the one axis in the control handle are mapped to bending of the colonoscope tip in two different directions [9]. Moreover, movement of the colonoscope tip requires bimanual action. While the left hand is used to steer the tip, the right hand is used to insert the colonoscope shaft. It is believed that this decoupling of control causes increased control complexity [10]. Furthermore, the control handle is large and suffers from poor ergonomics [11]. This is why many colonoscopists prefer the assistant to introduce the shaft while they control the handle with both hands. Literature suggests that improving intuitiveness saves time and lowers error rates [12], [13]. Hence, simplifying colonoscope steering principles can improve colonoscopy practice. By actuating the two control wheels of the colonoscope, an alternative user interface can be designed to control the tip intuitively. This can be done by using a setup as described in [14], [15].

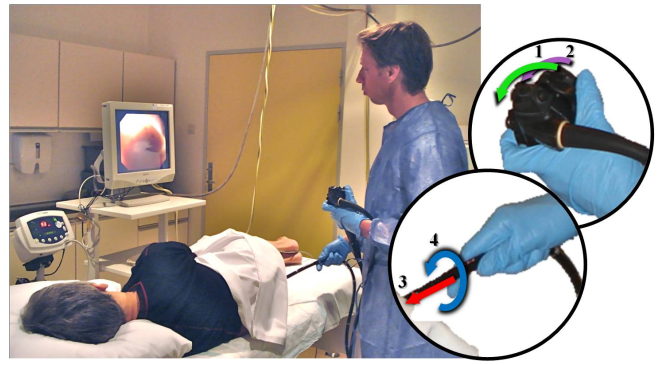

Fig. 1. A colonoscopist is performing a colonoscopy procedure at the Meander Medical Center (Amersfoort, The Netherlands) while he is looking at the images captured from the camera tip. With his right hand, he introduces the instrument into the bowel. With his left hand he operates the control handle that effectuates tip deflection. The arrows signify the degrees of freedom (DOFs) of the colonoscope.

In this study, we propose to control the colonoscope as if it were a rigid instrument with a camera on top. A user interface in the form of a grip was designed in collaboration with the gastroenterology department (Meander Medical Center, Amersfoort, The Netherlands). Colonoscope control with this user interface (which will be referred to as 'Grip' from now on) was tested for intuitivity using a colonoscopy simulator. Twelve novice subjects participated in the experiment.

This paper is structured as follows: in Section 1, the principles of conventional colonoscope control are described, followed by the design of the prototype for the Grip. To

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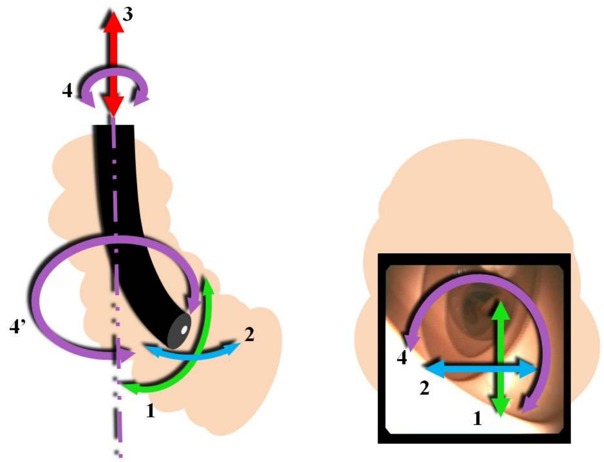

Fig. 2. **The DOFs of the colonoscope**: 1 and 2 show the result of turning the wheels at the control handle. They affect tip bending. DOFs 3 and 4 represent insertion and rotation of the colonoscope shaft at the anus. Torque steering can be done by operating only one wheel at the control handle (DOF 1 or 2) and controlling the tip by rotating the shaft. This results in a circular movement (4') if the tip is bent.

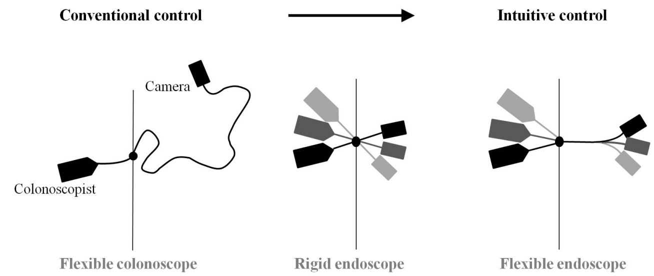

Fig. 3. Intuitive control is established by implementing a pivoting rigid endoscopic instrument analogy. In conventional colonoscopy, the wheels on the control handle effectuate the tip in which case the position of the control handle has no relation with the position of the tip. By implementing a pivoting rigid instrument analogy, the shaft position outside of the patient (relative to the anus) is used to steer the tip in a way that is similar to pointing a rigid instrument through a hole, as is done with rigid endoscopes in laparoscopy.

evaluate the control method, an experiment was done. This experiment and the results are described in Section III. Finally, in Section IV, a conclusion is drawn, results are placed in their clinical context and the future perspective of the proposed design is discussed.

II. Experimental setup

To learn about colonoscope control, the degrees of freedom (DOFs) of a conventional colonoscope are described and their use is briefly explained.

A. *Conventional colonoscope control*

Colonoscope tip steering consists of four degrees of freedom (DOFs) (Fig. 1). These are:

1) **Vertical tip bending**; controlled by turning the inner (large) steering wheel.
2) **Horizontal tip bending**; controlled by turning the outer (small) steering wheel.
3) **Longitudinal translation**; controlled by colonoscope advancement into the bowel.
4) **Rotation about the longitudinal axis**; controlled by rolling the shaft.

DOFs 1 and 2 are controlled by the wheels at the control handle that is typically operated by the left hand. The right hand holds the colonoscope shaft to control DOFs 3 and 4. If we assume that the two wheels actuate the tip independently with a similar range, the tip workspace for DOFs 1 and 2 will be a curved surface. DOF 3 allows translation of the tip along the longitudinal colonoscope axis. A rotation at the shaft (DOF 4) induces a pure rotation of the tip if it is not bent. In case it is bent, the tip will describe a circular motion as shown in Fig. 2. This DOF makes the tip over actuated: with DOFs 1-3, the whole workspace of the tip is already controlled. Thus, rotation of the shaft has no added value in positioning the tip. Typically though, DOF 4 is often used. In case the colonoscopist is unable to grasp the small steering wheel of the control handle, he/she replaces DOF 2 (small steering wheel) by rolling the shaft. This is called torque steering [16].

Furthermore, rolling the colonoscope shaft also plays an important role in the resolution and prevention of instrument looping, a situation that often occurs during a regular colonoscopy. If this happens, the colonoscope will form a loop inside the patient's bowel due to resistance along the colonoscope shaft between the tip and the anus. This is known to cause pain and bad instrument control. When looping occurs, simultaneously pulling back the colonoscope (DOF 3), rolling it (DOF 4) and applying suction while the tip is maximally bent (DOFs 1 and 2) is typically found helpful. This illustrates that all described DOFs should be controllable in the new control method [17].

Other functions of the colonoscope include inflation, suction and lens rinsing. These functions are important during colonoscopy to aid the introduction of the colonoscope [16].

B. *Demands/constraints*

On top of regular system demands for dependable use, special demands apply for this clinical application.

- **Functional**: The design should offer at least the same functionality as a regular colonoscope
- **Ergonomics**: Because control is no longer bound by mechanical transfer methods, considering ergonomics in design can lower the work related injuries that occur in colonoscopy[11].
- **Hygiene**: In the clinic, emphasis is put on preventing cross contamination.

To begin with, functional and ergonomic aspects were taken into account for our prototype. The next Section describes the means by which these aspects are optimized. Hygiene will be considered during later stages of design.

C. *Choice of concept*

According to Raskin, [9], intuitiveness is the extent to which we are familiar with a task. Colonoscope steering or performing similar tasks are not a daily practice, this is why

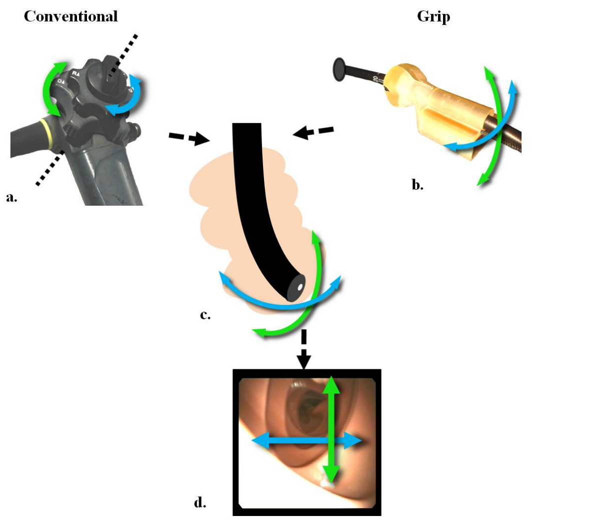

Fig. 4. The control mechanisms of a conventional colonoscope, a, and the Grip, b. Blue and green arrows resemble the matching DOFs in all four figures. **a**. The handle of a conventional colonoscope. Rotating the wheels (around the blue axis) actuates the tip by pulling the cables that run through the shaft. **b**. The Grip controls the tip in analogy to a rigid instrument. **c**. Last part of the colonoscope with it's flexible tip. **d**. The DOFs shown in a and b correspond to movement of the tip with respect to the camera image. Notice that in tip control 'up (camera)' stays 'up (control)', independent of rotation of the shaft.

conventional control of a colonoscope is assumed to be not intuitive [18], [19].

In order to establish intuitive control, the manipulation of DOFs 1 and 2 (tip bending) is changed. The orientation of the operator's hand is mapped to the orientation of the tip. The mapping will be analogous to a rod pivoting at a hole (Fig. 3). This form of control enables the colonoscopist to experience that movement of the colonoscope on one side of the anus translates to counter directed movement of the tip on the other side (Fig. 4).

The orientation of the operator's hand will be measured using a Grip equipped with an orientation sensor, that can slide over the colonoscope shaft. By adding a mechanical 'grasping' feature, all DOFs can be operated simultaneously. Besides increasing intuitiveness, the fact that total control can occur with one hand could improve user control even more [10]. Through the Grip, the colonoscopist remains 'in touch' with the forces along the colonoscope shaft. This is important to assess the occurrence of instrument looping and to prevent perforations. In designing the Grip, the thickness of the shell is important; it can reduce the torque that the colonoscopist needs to exert for DOF 4. This will positively affect the ergonomic aspects of colonoscopy [11].

D. Implementation

The Grip (Fig. 5) consists of two integrated parts. The sensor part contains a 3DOF orientation sensor (MTx, XSens Technologies, Enschede, The Netherlands) to allow orientation sensing. A flexible gripping part in front of the sensor enables the colonoscopist to rotate the shaft and introduce it into the colon. The friction that is created by pressing the ribs against the shaft enables advancement and rotation of the colonoscope, whereas relaxing the Grip allows sliding. Buttons are built in to operate the inflation, suction, and rinsing. The prototype was printed with a 3D printer (Objet Eden250 3Dprinter, material: FullCure 720).

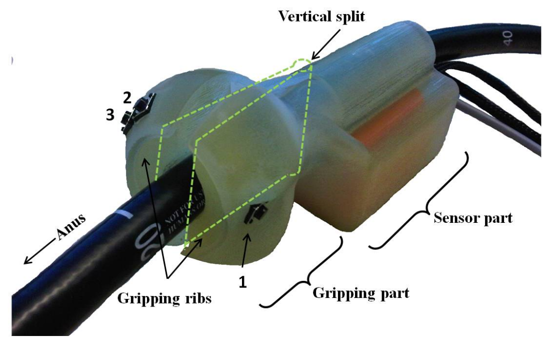

Fig. 5. The components of the Grip. The front part is the gripping part, the sensor part is integrally attached at the back. Also buttons for (1) Inflation, (2) deflation and (3) rinsing are added.

Mapping joint space to workspace: Horizontal and vertical deflection of the shaft are required to control the tip orientation (Fig. 7). The orientation of the sensor with respect to the world upon initialization is used to define a frame of reference, r. In this frame, the z axis of the sensor is parallel to the longitudinal axis of the colonoscope shaft. The orientation of the sensor with respect to the initial orientation is calculated as

$$ {}^{r}_{s}\mathbf{R} = {}^{w}_{r}\mathbf{R}^{-1} \cdot {}^{w}_{s}\mathbf{R}, \tag{1} $$

where ${}^{a}_{b}\mathbf{R}$ denotes a rotation matrix describing frame b relative to frame a. As described in the previous Section, DOFs 1 and 2 should not be influenced by DOF 4 (rolling the colonoscope over the z axis). This is realized by projecting the z-axis of frame s (denoted as $\mathbf{D}$) onto the x- and y-axis of frame r. These projections are denoted as D_x and D_y respectively (Fig. 7).

The input angles are scaled such that maximum tip bending is reached when the horizontal or vertical angles of the sensor exceed approximately $50°$. For all angles between $-50°$ and $+50°$, horizontal and vertical deflection control the tip linearly.

The sensor is known to exhibit drift in the orientation in the horizontal plane [20]. This could cause problems, as this is one of the measures that are used for control. A re-initialization function was programmed that resets the reference frame r of the sensor to the current orientation of the sensor.

Operating the buttons the buttons on the Grip is similar to the conventional setting; three tactile buttons operate inflation, suction and rinsing.

Control loop: The control diagram (Fig. 6) shows the control loop for the Grip. The operator is provided with several types of feedback to support steering during the procedure. Firstly he/she receives input from the monitor where the tip camera image is shown. Secondly, a separate monitor shows a tip bending diagram. This diagram informs the colonoscopist about the extent to which the tip is bent.

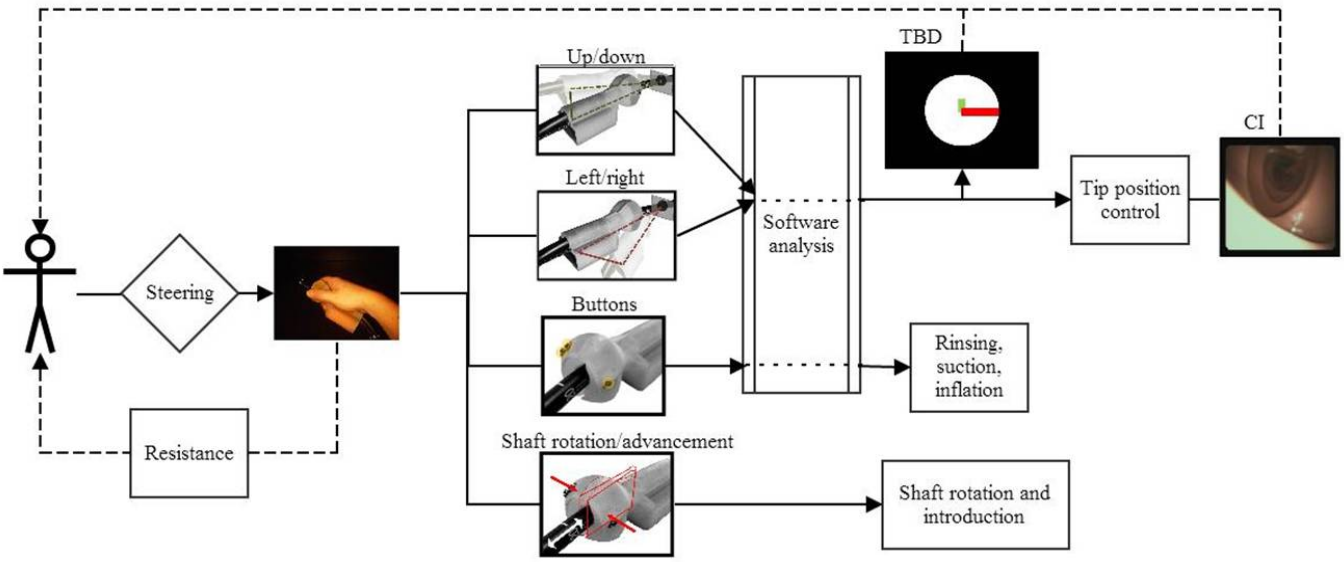

Fig. 6. Control diagram that shows user control guided by force perception of the shaft and several types of visual feedback. Like in normal colonoscopy, the camera image (CI) is shown. Furthermore, a tip bending diagram (TBD) is offered that indicates the amount of tip bending in both directions. It is offered to the user as a replacement for haptic feedback at the conventional control handle. Steering is performed by vertical and horizontal movements of the Grip. Shaft advancement and rotation are manually controlled. Rinsing, suction and inflation are operated by buttons.

In conventional colonoscopy, the operator can deduct this information from the resistance on the wheels, whereas with the Grip this is not possible. The diagram shows two bars: vertical and horizontal (for vertical and horizontal bending) that are displayed in a white circle. The bars grow to a maximum when the tip is maximally bent. Besides increasing in length, the bars also turn more red as the angles increase. Finally the operator is supported by haptic feedback in the form of resistance that he/she feels when moving the shaft. This informs him/her about the shape of the shaft. Based on these inputs, the operator can steer the colonoscope tip through the lower gastrointestinal tract.

III. Evaluation

To assess the added value of the Grip over conventional colonoscopy, we have conducted a human subject experiment.

A. Study design

For testing purposes, a simulation case of a validated colonoscopy simulator (Accu Touch, Immersion Medical, San Jose, California) was used [21]–[23]. The simulator provides a reproducible colonoscopy environment and quantitative output measures that are associated with colonoscopy competence. We have used Case 1 of the lower GI module (introduction). In colonoscopy, introduction of the colonoscope is the first part of the procedure after which, during withdrawal, the extensive visual inspection of the colon is done. In steering, the introduction part is considered the most difficult. Therefore, the introduction time (IT) is taken as our primary output measure. This is defined as the time required to reach the caecum.

We expect the use of the Grip to yield steeper learning curves and lower IT. To assess the learning effect, performance is measured at two points in time with one to five days in between. The two measurements were each taken after a training session of thirty minutes. The training sessions were all conducted by the same researcher who supplied the equivalent instructions to all subjects. At the time of the measurements the subjects were asked to perform an optimal introduction of the colonoscope. They were told that IT was important, but that a perforation should be avoided at all times.

The simulator gives information similar to the information that the colonoscopist receives during a real colonoscopy. Thus, the tip endoscopic image is shown as well as vital functions like heart rate and saturation. Via speakers, heart rate is heard as an intermittent beep and the simulator provides vocal expressions of discomfort. Tactile feedback is also presented in the form of realistic shaft resistance. During the training session, the subject receives feedback (performance measures, e.g. procedure time, pain, and insertion depth) from the simulator at any desired moment, and always after the caecum is reached. Furthermore, colonoscope position feedback is supplied upon request by using the ‘external view’ function of the simulator. Upon calling this function, the simulator shows a picture of the shape of the whole colonoscope inside the bowel. This information is relevant in learning how to resolve colonoscope looping. During the actual measurement, this information is not supplied because it is generally not available during a clinical colonoscopy.

B. Subjects

The subjects were third and fourth year Technical Medicine[1] students who had no experience in performing any

[1] Technical Medicine is a master’s degree program at the University of Twente in which the students learn both medical and technical subjects.

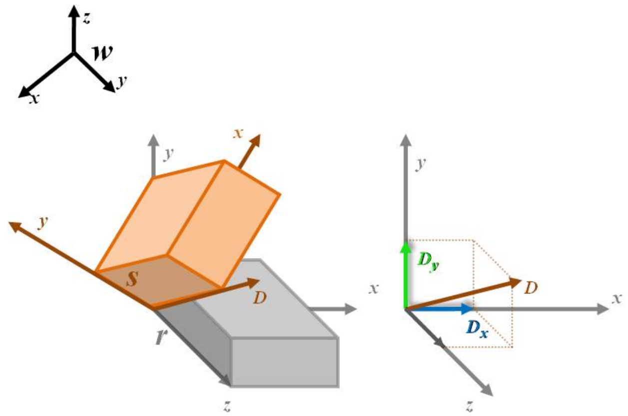

Fig. 7. World frame (w), reference frame of sensor (r) and rotating actual sensor (s). The projection of D on the x-axis and y-axis of s is used as the control input for horizontal and vertical tip movement.

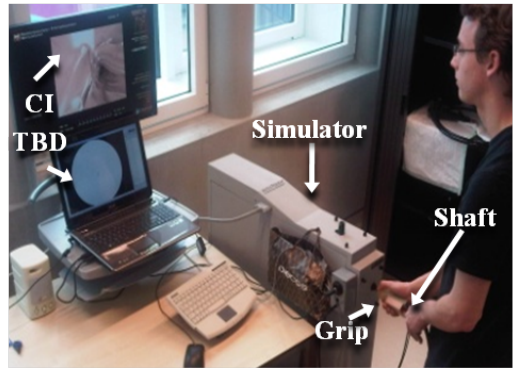

Fig. 8. Test setup shown for a subject using the Grip. The subject pushes the shaft into the simulator (usually with the Grip that is held by the right hand and sometimes assisted with the left hand). During the colonoscope introduction the subject is guided visually by the camera image (CI) and the tip bending diagram (TBD). For the conventional group, the Grip was replaced by the control handle and the tip bending diagram was not displayed.

form of endoscopy, but had sufficient knowledge of anatomy. All 12 subjects gave informed consent. There were 7 male and 5 female students. Their ages were between 21 and 25 years (average 22 years). They were alternately assigned to a group using conventional steering (conventional group) or to a group using the Grip (Grip group). They received no financial compensation for their participation.

C. Data analysis

The IT is considered the most important measure for competence [21], [23]. A pain score that is measured by the simulator is also collected. Although pain is still not a validated measurement for competency [23], it will be evaluated to rule out a potential trade-off in speed versus accuracy. The pain scores were measured as five categories: no, mild, moderate, severe and extreme discomfort. They were measured in seconds and expressed as fractions of the IT. These fractions were combined linearly in order to obtain a single measure. A weight from 0 to 4 was assigned to each category (no discomfort = 0, extreme discomfort = 4). In order to evaluate the learning curve, a paired student t-test (two-sided) was carried out in which measurements of subjects are paired and the learning effects of both groups were compared. Although two measurements can hardly be expected to yield a valid learning curve (in conventional colonoscopy, over 50 procedures are needed), this can be considered a pilot experiment. Also, the measure of intuitiveness of both control methods will be evaluated by comparing the difference of means of both groups (t-test). To rule out a possible speed-accuracy tradeoff, a Pearson correlation is calculated for IT and pain score. The level for significance is set at 0.10. Subjects who caused a perforation of the bowel are excluded from the analysis.

D. Results

None of the subjects caused a perforation during the measurements. The results for the IT are shown in Fig. 9. The mean IT for the whole group (all measurements) is 352 seconds, with a standard deviation of 155 seconds.

No significant difference between groups was found in the improvement of the IT between the first and the second measurements. The two groups combined show a 97 seconds (24%) faster introduction during the second measurement ($p = 0.06$).

Comparing the first measurements of the groups, the Grip group is 172 seconds faster than the conventional group, however this difference was not significant ($p = 0.11$). In the second measurement, the Grip group performed 156 seconds faster than the conventional group ($p < 0.005$). On average, the Grip group is 38% faster compared to the conventional group ($p = 0.006$). Evaluation of the pain scores show no significant speed-accuracy tradeoff for the whole group (Pearson $= -0.31, df = 22, n.s.$), nor for the conventional group (Pearson $= -0.06, df = 10, n.s.$) nor for the Grip group (Pearson $= -0.44, df = 10, n.s.$).

IV. Conclusion and Discussion

The proposed Grip enables the colonoscopist to operate all functions that a standard colonoscope offers. The results of the experiment show that novice subjects perform a faster introduction using the Grip. There does not seem to be a trade-off relation between pain scores and IT.

Current clinical practice: The Grip group performed 38% faster on average compared to the subjects using the conventional control handle. The initial better results with the Grip show that this control method is more intuitive. Implementation of 'Grip control' will possibly decrease the required training time for colonoscopy. Moreover, because of simple steering, the Grip might have a positive effect on the quality of the procedure in terms of functionality, ergonomics, pain and complications.

With this technology, colonoscopy can become more easy and might therefore become part of the work of a broader range of medical personnel. This can lower the cost of a colonoscopy since the extra costs will only be made on behalf of the Grip and the module that actuates the colonoscope.

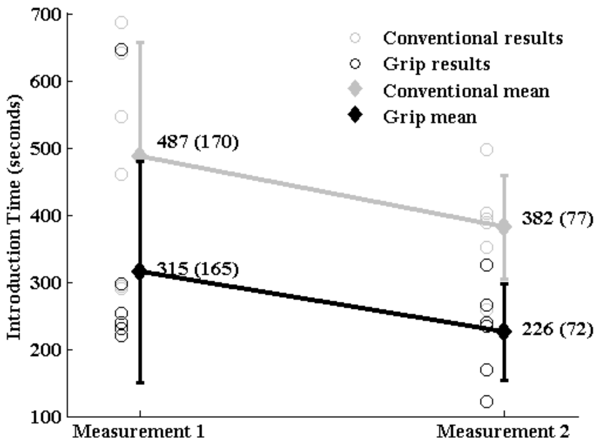

Fig. 9. Results of introduction time (IT) for the two groups: conventional and Grip. The individual measurements as well as the group averages and standard deviations are shown. The error bars indicate one standard deviation (shown between brackets) on each side of the mean. For each group, the results of both measurements are shown. The learning effect between the first and second measurement does not differ between both groups, whereas initial competence (or intuitivity) is better for the interface using group.

With this cost saving prospect, screening for CRC may become economically beneficial.

Future applications: The Grip opens up possibilities for more applications since the restrictions of the conventional control handle will no longer apply. Different types of Grips can be used for different endoscopic procedures. Additionally, colonoscopists with preferences for sensitivity of control or left- or right-handedness may choose a custom Grip.

Future work: The current prototype of the Grip leaves room for some improvements. The most essential refinement will be to revise the way orientation data is obtained. The sensor is known to suffer from drift in the horizontal plane. This problem needs to be solved since it is unacceptable in the clinic. Also, the material from which the Grip was constructed will be optimized to comply with hygiene guidelines and for optimal material properties. Finally, a module that actuates the colonoscope needs to be developed. The development will focus on producing a safe, efficient and user friendly solution for the clinic.

V. Acknowledgments

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