The International Journal of **Medical Robotics** and **Computer Assisted Surgery**

THE INTERNATIONAL JOURNAL OF MEDICAL ROBOTICS AND COMPUTER ASSISTED SURGERY
*Int J Med Robotics Comput Assist Surg* 2013; **9**: 240–246.
Published online 23 April 2013 in Wiley Online Library (wileyonlinelibrary.com) **DOI:** 10.1002/rcs.1496

**ORIGINAL ARTICLE**

# Evaluation of robotically controlled advanced endoscopic instruments

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*Accepted: 28 January 2013*

## Abstract

**Background** Advanced flexible endoscopes and instruments with multiple degrees of freedom enable physicians to perform challenging procedures such as the removal of large sections of mucosal tissue. However, these advanced endoscopes are difficult to control and require several physicians to cooperate.

**Methods** In this article, we present a robotic system that allows the physician to control an instrument in an intuitive way, using a haptic device. Performance with the robotic and conventional control methods were compared in a human subjects experiment. Subjects used both methods to tap a series of targets. They performed four trials while looking at the endoscopic monitor, and two trials while looking at the instrument directly.

**Results** Subjects were significantly faster using the robotic method, 54 s vs 164 s. Their performance in the second trial was significantly improved with respect to the first trial.

**Conclusions** This study provides evidence that the robotic control method can be implemented to improve the performance of physicians using advanced flexible endoscopes. Copyright © 2013 John Wiley & Sons, Ltd.

**Keywords** flexible endoscopy; minimally invasive surgery; medical robotics

## Introduction

Flexible endoscopy is a minimally invasive procedure that enables the physician to examine the digestive tract of a patient. It also allows for small interventions, such as biopsies and polyp removal. However, more advanced procedures, such as the removal of larger sections of mucosal tissue, are challenging due to the limited dexterity of the endoscopic instruments. In order to overcome this limitation, advanced endoscopic instruments are currently being developed; these advanced instruments have a greater dexterity. They include the Anubis endoscope (Karl Storz GmbH & Co. KG, Tuttlingen, Germany) and the EndoSamurai (Olympus Corp., Tokyo, Japan). These endoscope systems have the dexterity that would also make them suitable for natural orifice translumінal endoscopic surgery (NOTES) (1).

However, the aforementioned endoscopes are difficult to use. Multiple physicians are required to control the endoscope and the instruments (1). This is undesirable, since coordination is difficult, and because of associated costs. Furthermore, the control of the endoscope and the instruments is not intuitive, their interface is not ergonomic and there is significant hysteresis present in the controls which limits the accuracy. A teleoperated set-up, in

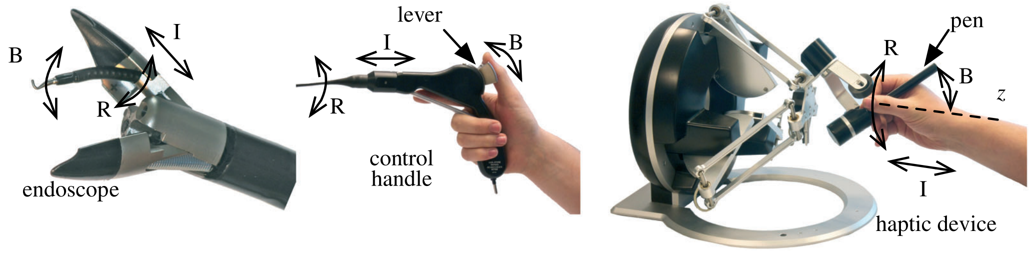


**Figure 1. The Anubis endoscopic instruments have three degrees of freedom, insertion (I), rotation (R) and bending (B). For the conventional method, these are controlled by moving the control handle forwards and backwards (I), by rotating the control handle (R) and by using the bending lever (B). For the robotic method, these are controlled by moving the haptic device forwards and backwards (I), by rotating the pen around the *z* axis (R) and by rotating the pen away from the *z* axis (B)**

which a single physician controls all degrees of freedom (DOFs) of the endoscope system, could overcome these issues (2,3).

In order to control the instruments accurately, the hysteresis that is present in these instruments needs to be reduced. This can be done using an external sensor (4), by measuring the hysteresis pre-operatively as described by Abbott *et al*. and Bardou *et al*. (3,5) or by estimating the instrument position from the endoscopic images (6). The latter method is advantageous because no external sensors are required, and it can adapt to variations in the hysteresis parameters that may occur during the intervention.

The aforementioned studies show that it is possible to control an endoscopic instrument accurately. However, whether there is a performance gain for the physician has not been evaluated, i.e. whether the proposed methods are better than conventional control of the instruments in the tasks that need to be performed. In this study, we present a human-subjects experiment that compares robotic teleoperated control of flexible instruments with conventional control (Figure 1).

This paper is structured as follows. The Materials and methods section describes the robotic and the conventional control methods and presents the experimental evaluation. Subsequently, the Results of the experimental evaluation are presented. The paper concludes with a Discussion.

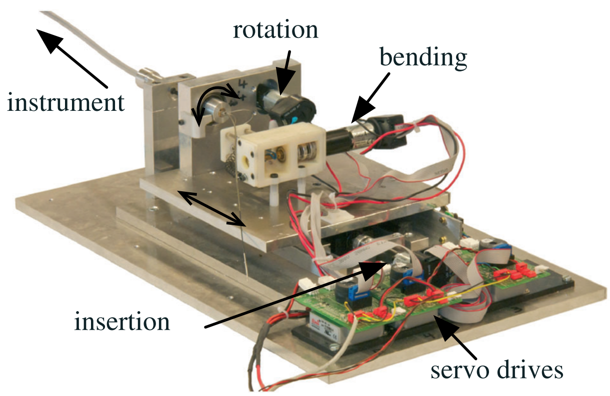


**Figure 2. Actuation of the instrument: three motors actuate the insertion, rotation and bending DOFs of the instrument. The motors are controlled by servo-drives**

# Materials and methods

In order to evaluate the robotically actuated instruments, a human subject experiment is performed. This section describes the endoscopic instruments, and the robotic control of these instruments. The experimental procedure is also described.

## Advanced endoscopic instruments

For this study, an instrument of the Anubis endoscope system (Karl-Storz GmbH & Co. KG) is used. It has three DOFs, as indicated in Figure 1: insertion (I), rotation (R) and bending (B). The instrument is designed to be operated manually. The control handle can be moved forwards and backwards to insert and retract the instrument, and it can be rotated to rotate the instrument around its axis. The bending of the instrument is controlled by a lever that is operated by the thumb.

## Robotic control of the instrument

A set-up is used that allows actuation of all three DOFs of the endoscopic instrument (Figure 2). The DOFs are driven by three DC motors (A-Max 22, Maxon, Sachseln, Switzerland), which are controlled by Elmo Whistle servo amplifiers (Elmo Motion Control, Petach-Tikva, Israel). The set-points for the DOFs are generated by a laptop computer (Macbook Pro, 2 GHz Core i7, Apple, Cupertino, USA).

When the instrument is controlled robotically, the hysteresis that is present in the instrument can be reduced to improve the performance. To do this, the hysteresis is modelled similar to Lagerberg and Egardt (7). The model is hybrid, with three discrete modes: negative contact, free, and positive contact (Figure 3). We use $c$ to denote the actuator position and $q$ to denote the instrument position, and $\dot{c}$ and $\dot{q}$ as their time derivatives, respectively. The instrument motion is given by:

$$\dot{q} = \begin{cases} \min(\dot{c}, 0), & q = c + \delta^- & (negative\ \ contact) \\ 0, & c + \delta^- < q < c + \delta^+ & (free) \\ \max(\dot{c}, 0), & q = c + \delta^+ & (positive\ \ contact) \end{cases} \tag{1}$$

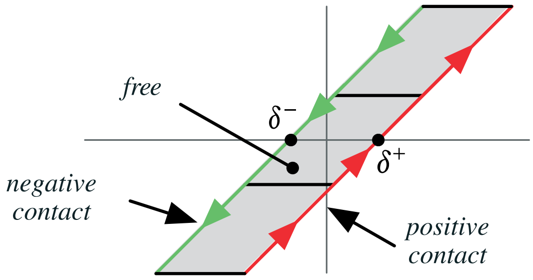


**Figure 3. Hysteresis model: in the positive contact and negative contact modes, the instrument motion *q* follows the actuator motion *c*. In the free mode, the instrument is stationary**

where $\delta^-$ and $\delta^+$ represent the negative and positive contact positions, respectively.

In order to reduce the hysteresis, a common approach is to tranverse the free region by applying a predefined trajectory to the actuator whenever the direction of the motion changes (7,8). However, when the instrument is telemanipulated, the direction of motion changes, often due to tremor, when small movements are performed. The use of a predefined trajectory would result in a 'nervous' behaviour, i.e. rapid motions of the actuator while the instrument is almost stationary. Therefore, we use a limited-gain compensation in which the actuator motion is a fixed multiple of the input motion:

$$\dot{c} = \begin{cases} \dot{u} & \text{in } \textit{contact} \text{ mode} \\ K\dot{u} & \text{in } \textit{free} \text{ mode} \end{cases} \tag{2}$$

in which $K$ is the gain ($K = 5$) and $\dot{u}$ denotes the motion of the telemanipulation input device. This ensures that the actuator motions are limited, preventing undesired 'nervous' behaviour. This hysteresis compensation is applied independently to all three DOFs.

For the current study, we have used pre-identified values for $\delta^-$ and $\delta^+$. However, since in clinical practice these values may change during the procedure, alternative online estimation of these values could be implemented. The hysteresis can be estimated by comparing the actuator motion and the motion of the instrument tip; the latter can be obtained from the endoscopic images (6). This method requires no external sensors to be added to the instrument.

## Experimental methods

The robotic instrument control method that was described in the previous section was compared to conventional control using a tapping experiment. In the experimental evaluation, subjects used both methods to tap on fixed targets. As opposed to Golenberg *et al.* (9), who used a flat surface with targets, we have constructed a three-dimensional (3D) environment that contains the targets. This environment was constructed from a Plexiglass tube of 110 mm diameter. The endoscope was rigidly attached to this tube, as shown in Figure 4. Three targets were located in the workspace of the endoscopic instrument. They were positioned such that the subjects

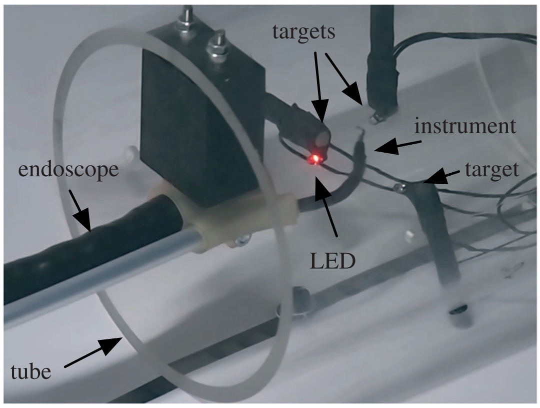


**Figure 4. The environment for the experiment consisted of a transparent tube with three targets. The endoscope was fixed to the tube. LEDs were used to signal the subject which target was to be tapped**

would need to manipulate all three DOFs of the instrument in order to reach from one target to the next. Each target consisted of a metal bolt of 4 mm diameter. The sides of the bolt were covered, to force the subjects to actually tap the top of the target, as opposed to sliding the instrument tip along the side of the target. An orange light-emitting diode (LED) next to each target was used to show which target to tap. A circuit was built to detect electrical conductance between the tip of the instrument and the target in order to register when a tap was successful.

A conventional colonoscope was used for the experiment (Exera, Olympus Corp., Tokyo, Japan). A tip attachment was designed to guide the instrument (Figure 5). The position and orientation of the instrument with respect to the endoscope are identical to the Anubis endoscope system.

## Experimental conditions

The control of the endoscopic instruments was evaluated using four experimental conditions. These four conditions are the combinations of two methods and two ways of viewing the environment. The two methods are robotic

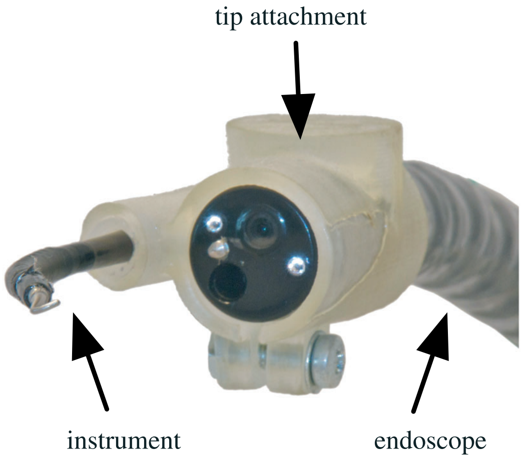


**Figure 5. A tip attachment is fitted to the tip of the endoscope in order to guide the instrument**

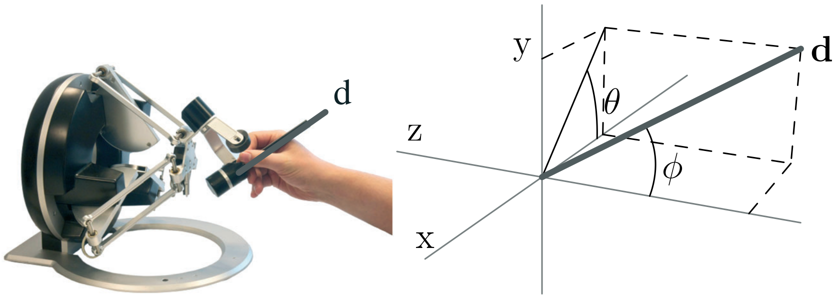


**Figure 6. The direction of the pen of the haptic device (d) controls the bending and rotation DOFs. The angle ϕ controls the bending. The angle θ controls the rotation**

and conventional. The two ways of viewing the experimental environment are endoscopic view and direct view. These methods and views are described below.

## Robotic method

In the robotic method, the endoscopic instrument is controlled by an Omega 6 haptic device (Force Dimension, Nyon, Switzerland). Insertion (I) is controlled by moving the pen of the Omega 6 forwards and backwards. The orientation of the pen controls the rotation (R) and bending (B), such that the orientation of the instrument tip will match the orientation of the Omega 6 pen. This is realized as follows. The direction vector of the pen is indicated by **d** (Figure 6). The bending is controlled by the angle between **d** and the $z$ axis, denoted by $\phi$. The rotation is controlled by the rotation around the $z$ axis, i.e. the angle between the $x$ axis and the projection of **d** onto the $x$–$y$ plane. This angle is denoted $\theta$.

The force-feedback capabilities of the Omega 6 are used to limit the translation of the device to the forward/backward ($z$) direction. Translations away from the $z$ axis are counteracted by virtual springs. Figure 8 shows the set-up in use with the robotic method.

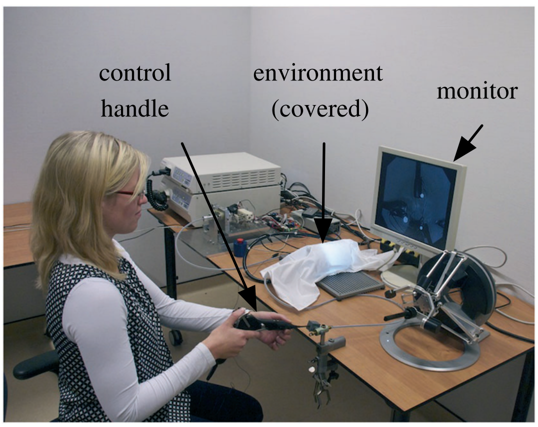


**Figure 7. Subject performing the experiment using the conventional method under the endoscopic view condition**

## Conventional method

In the conventional method, the endoscopic instrument is controlled using the conventional control handle, as shown in Figure 1. The instrument is inserted into a flexible outer tube that guides the instrument into the endoscope tip attachment. The proximal end of this tube is fixed to the table. Insertion (I) is controlled by inserting the instrument into the outer tube. Rotation (R) is controlled by rotating the control handle. Bending (B) is controlled by a lever on top of the handle that is operated by the thumb. Figure 7 shows the experimental set-up in use with the conventional method.

## Endoscopic view

In the endoscopic view condition, the scene is captured by the flexible endoscope. The subject observes the scene on a flat screen monitor. The Plexiglass tube is covered by a white cloth to ensure that the subject cannot see the scene directly and also ensures that the endoscopic view does not contain anything that is outside the Plexiglass tube; furthermore, the white cloth improves the lighting of the scene and, thus, the image quality. The endoscopic view condition is shown in Figure 7. Figure 8 shows the endoscopic image that is displayed on the monitor.

## Direct view

In the direct view condition, the subject looks at the scene directly. The endoscope camera system is switched off. This allows the subject to observe the scene in 3D, as opposed to the two-dimensional (2D) view that is shown on the monitor in the endoscopic view condition. Although the direct view condition is not of clinical relevance, it was included to find out whether the lack of 3D vision in the endoscopic view condition was of significant influence. The direct view condition is shown in Figure 9.

## Procedure

Each subject was instructed using a prerecorded video; this ensured that all subjects received the same instructions. The video showed the subject how to manipulate

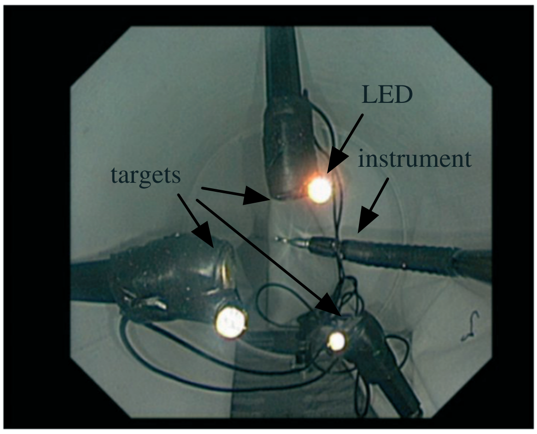


**Figure 8. In the endoscopic view condition, the subjects observe the environment on the endoscopic monitor**

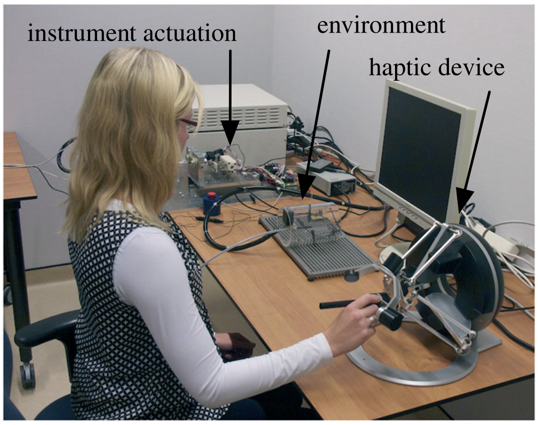


**Figure 9. Subject performing the experiment using the robotic method under the direct view condition**

the instruments using both conventional and robotic methods, and showed a successful tapping sequence.

After watching the instruction video, the subject performed an experimental session using each of the two methods, while viewing the environment on an endoscopic monitor (Figure 4b). The orders in which the methods were used were counterbalanced over the subjects. Each session was composed of four trials consisting of seven taps each, with a small break between the trials. There are six possible paths from one target to the next (from target 1 to 2, from 2 to 3 etc.). The tapping sequences were such that, after the first tap, each of the six possible paths was transversed exactly once. In each subsequent trial, the order of the taps was different to ensure that the subjects would not know in advance which would be the next target. The orders were the same for each subject.

When the subject made contact with the target, they were given audible feedback. In order to obtain a successful tap, they needed to remain in contact for 400 ms. This was done to prevent accidental touches from being registered as a successful tap. After the 400 ms period, another audible feedback signal was given. After the two methods were evaluated using the endoscopic view, the subjects repeated the sessions while observing the environment directly (direct view). In this case they performed two trials of seven taps for each of the two methods. The complete experiment took 30–45 min/subject.

All subjects started with the endoscopic view condition, because this one is the most clinically relevant. Of course, this may create a bias towards lower completion times for the direct view condition, due to learning effects. However, the hypothesis was that subjects will perform better with the direct view condition, due to the presence of stereoscopic vision. Thus, if indeed subjects do perform better with the direct view condition, it cannot be concluded whether this is due to learning or due to the presence of stereoscopic vision. If there are no significant differences between the two view conditions, this will suggest that the presence of stereoscopic vision is not of major influence.

## Subjects

Sixteen subjects participated in the experiment. The subjects were senior Technical Medicine[1] students who had completed a training in rigid and flexible endoscopy. As such, they were acquainted with instrument manipulation and the lack of stereoscopic vision during the procedure. There were four male and 12 female subjects, aged 22–26 years, with an average age of 24 years. All subjects were right-handed. All subjects had normal stereopsis, as was confirmed by a stereopsis test prior to the experiment (10). The subjects participated on a voluntary basis and signed an informed consent form. They received financial compensation for their participation (€10).

# Results

Figure 10 shows the average completion time for each trial per method. The completion times for each trial were compared using a repeated-measures analysis of variance (ANOVA). For the endoscopic view condition, significant effects were found for method [$F(1, 15) = 35.25$, $p < 0.001$], trial [$F(3, 45) = 13.20$, $p < 0.001$] and method × trial interaction [$F(3, 45) = 3.23$, $p = 0.02$]. The robotic method had a significantly lower average completion time than the conventional method, 54 and 164 s, respectively. Subsequent pairwise comparisons with Bonferroni correction for multiple comparisons showed that the first trial was significantly slower than the other trials ($p < 0.05$). There were no significant differences found between the second and subsequent trials.

Figure 10 suggests that the rate at which the completion times decrease for each trial is different for the two methods. This is supported by the significant method × trial interaction effect. Therefore, we performed a linear least squares fit of the completion time results. For each

[1]Technical Medicine is a Master's level programme in which students study to integrate advanced technologies within the medical sciences to improve patient care.

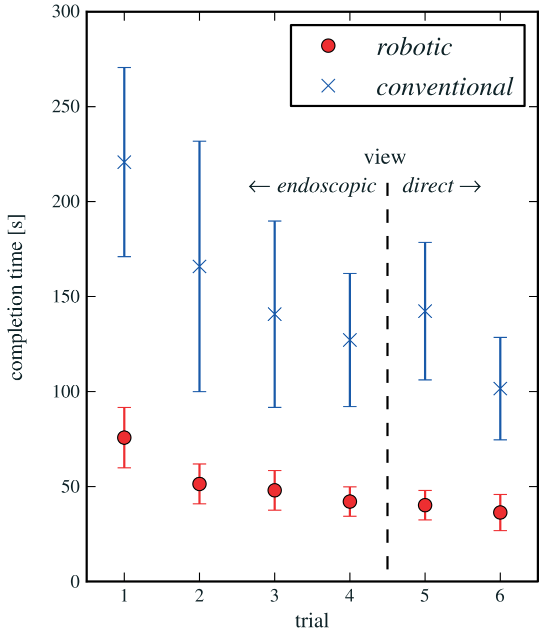


**Figure 10. Results: the robotic method had a lower average completion time than the conventional method for each trial. There was a significant learning effect between the first and second trials. Trials 1–4 were performed under the endoscopic view condition, while trials 5 and 6 were performed under the direct view condition. Error bars indicate the 95% confidence interval**

subject, and for both methods, the four trial completion times were fitted to the linear model:

$$t_c = \alpha n + \beta \quad (3)$$

where $t_c$ denotes the completion time, $n$ indicates the trial number ($n = 1..4$) and $\alpha$ and $\beta$ are fitting constants. We performed a repeated measures analysis on the resulting slopes $\alpha$. A significant influence of the method on $\alpha$ was found [$F(1, 15) = 16.06$, $p = 0.03$]. The mean $\alpha$ was $-10$ s/trial for the robotic method and $-30$ s/trial for the conventional method. Thus, there was a significantly faster improvement in the conventional method than in the robotic method.

The endoscopic view and the direct view conditions were compared using a repeated-measures ANOVA on the completion time of the last trial of each method (i.e. trial 4 for the endoscopic view and trial 6 for the direct view). No significant differences were found.

## Discussion

Two methods for control of advanced multi-DOF endoscopic instruments were compared, using a tapping experiment. It was found that the average task completion time was significantly lower for the robotic method than for the conventional method. It was found that for the conventional method, the improvement in completion times was higher than for the robotic method. This is probably due to the fact that with the robotic method the learning process is already nearly finished after a few trials, and thus there is hardly any room for further improvement.

From the current experiment, the lowest completion time that the subjects could achieve after performing many trials could not be determined. Possibly, subjects are able to achieve similar completion times using both methods if they learn more by performing additional trials. To determine the ultimate performance would require another experiment in which the subjects perform more trials. However, even if similar completion times could be achieved using both methods, it would still be favourable to use robotic control. It is more intuitive and its ergonomics can be optimized by tuning the mapping between the haptic device and instrument motions. Furthermore, robotic control is more suitable to use in an integrated system in which both the endoscope and the instruments can be controlled by a single physician.

No significant differences were found between the endoscopic view and the direct view conditions. Thus, the lack of stereoscopic vision seems of little influence during this experiment. All subjects performed the endoscopic view condition first, and then the direct view condition. This could create a bias towards lower completion times for the direct view condition, due to learning effects. However, the presence of stereoscopic vision in the direct view condition was hypothesized to also lower the completion time for the direct view condition. Yet, no significant differences in completion time were found, and thus there is no indication that the direct view condition reduces the completion time. It was noticed that the subjects who already had experience with (simulated) endoscopic procedures were well capable to deal with the lack of stereoscopic vision. When they moved the instrument in front of or behind one of the targets, they could correct this quickly and then hit the target.

Future work will be focused on the design of an integrated teleoperated endoscope system, in which a single physician can control all DOFs of an advanced flexible endoscope and two advanced endoscopic instruments. In a previous study we have shown the feasibility of robotic control of the endscope tip (11). The current study has shown that robotic control is a suitable method for teleoperating the instruments. This integrated teleoperated endoscope system will enable the physician to perform endoscopic interventions that require a higher degree of dexterity than is available with current flexible endoscopes.

## Acknowledgements

This research was conducted within the TeleFLEX project, which is funded by the Dutch Ministry of Economic Affairs and the Province of Overijssel, within the Pieken in de Delta (PIDON) initiative. The Anubis endoscopic instrument was provided by Karl Storz GmbH & Co. KG, Tuttlingen, Germany. The endoscope was provided by Olympus Corp., Tokyo, Japan.

## Conflict of Interest

The authors have declared that there is no conflict of interest

## References

1. Marescaux J, Dallemagne B, Perretta S, *et al*. Surgery without scars: report of transluminal cholecystectomy in a human being. *Arch Surg* 2007; **142**(9): 823–826.
2. Bardou B, Nageotte F, Zanne P, *et al*. Design of a telemanipulated system for transluminal surgery. In 31st Annual International Conference of the IEEE EMBS, 2009.
3. Abbott D, Becke C, Rothstein R, *et al*. Design of an endoluminal NOTES robotic system. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), San Diego, CA, USA, 2007; 410–416.
4. Bardou B, Zanne P, Nageotte F, *et al*. Control of a multiple sections flexible endoscopic system. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Taipei, Taiwan, 2010; 2345–2350.
5. Bardou B, Nageotte F, Zanne P, *et al*. Improvements in the control of a flexible endoscopic system. In Proceedings of the IEEE/RSJ International Conference on Robotics and Automation (ICRA), St. Paul, MN, USA, 2012; 3725–3732.
6. Reilink R, Stramigioli S, Misra S. 3D position estimation of flexible instruments: marker-less and marker-based methods. *Int J Comput Assist Radiol Surg* 2012 [published online October 2012]. DOI: 10.1007/s11548-012-0795-1
7. Lagerberg A, Egardt BS. Estimation of backlash with application to automotive powertrains. In Proceedings of the 42nd IEEE Conference on Decision and Control, Maui, Hawaii USA, 2003; 4521–4526.
8. Bardou B. Développement et Étude d'un Système Robotisé pour l'Assistance à la Chirurgie Transluminale. PhD Thesis, Université de Strasbourg, 2011.
9. Golenberg L, Cao A, Ellis RD, *et al*. Hand position effects on precision and speed in telerobotic surgery. *Int J Med Robot* 2007; **3** (3): 217–23.
10. TNO. TNO Test for Stereoscopic Vision. Laméris Ootech BV: Nieuwegein, Netherlands, 1972.
11. Reilink R, Stramigioli S, Kappers AML, *et al*. Evaluation of flexible endoscope steering using haptic guidance. *Int J Med Robotics Comput Assist Surg* 2011; **7**(2): 178–186.