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Intuitive user interfaces increase efficiency in endoscope tip control

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Abstract
Background Flexible endoscopes are increasingly used to perform advanced intraluminal and transluminal interventions. These complex interventions demand accurate and efficient control, however, current endoscopes lack intuitiveness and ergonomic control of the endoscope tip. Alternative handheld controllers can improve intuitiveness and ergonomics, though previous studies are inconclusive concerning their effect on the efficiency of endoscope manipulation. The aim of this study is to determine the efficiency of a robotic system with intuitive user interface in controlling the tip of the flexible endoscope.
Methods We compared the efficiency of time and tip trajectory when steering the endoscope tip using the conventional steering wheels and a robotic platform with three different user interfaces: a touchpad in combination with a position control algorithm, a joystick combined with linear rate control, and a joystick combined with non-linear rate control. Fourteen participants, without a medical background, used all four interfaces. They performed both large navigational and fine targeting tasks in a simulated environment which allowed objective cross-subject comparison. Afterward, the participants were asked to select their preferred steering method.
Results Participants were significantly faster in steering the endoscope tip when using robotic steering compared to using the conventional steering method. Between the robotic interfaces, using the touchpad was significantly faster compared to the joystick with linear rate control. Use of the joystick with non-linear rate control led to a shorter tip trajectory compared to the touchpad. The majority of participants preferred the joystick with non-linear rate control over the other steering methods.
Conclusions This work shows that intuitive user interfaces can improve the efficiency of endoscope tip steering.

Keywords Flexible endoscopy · Intuitive · Ergonomic · Joystick · Touchpad · Efficiency

Flexible colonoscopes are increasingly used in advanced intraluminal and transluminal therapeutic interventions [1–4]. These complex interventions demand accurate and efficient control of the endoscope and its accessories [1, 5, 6]. The endoscope tip can be controlled by a combination of scope advancement, shaft rotation, and tip angulation. Combining these movements is already difficult in diagnostic procedures, and complexity only increases with interventions [6–8]. Furthermore, the endoscope's poor intuitiveness and ergonomics introduce a long learning curve to achieve hands-on competence and cause musculoskeletal complaints [9]. Robotics allow the introduction of intuitive and ergonomic user interfaces that can address these difficulties in tip steering [10, 11] and may reduce the dependence on technical skills.

However, recent studies remain inconclusive concerning the effects of a robotic setup with intuitive interfaces on efficiency of endoscope manipulation [12–14]. Allemann et al. [12] report that both novices and experts required significantly more time to complete a maneuvering task when

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using a joystick compared to using the conventional system. They ascribed this outcome to the limited maneuverability of the setup and the used control algorithm [10]. Reilink et al. [13] showed that experts perform faster cecal intubation, while novices show no significant difference, when performing simulated colonoscopy using the conventional steering method versus an intuitive interface. They expect improvements with learning and adaptations to the described interface. Eckl et al. [14] found no significant difference in the efficiency of novices bending a flexible rhino endoscope whether using a joystick or the conventional control method. In summary, there are inconclusive results and the used control setup is vital to the outcome.

We analyzed the efficiency of the robotic system with intuitive interfaces described by Ruiter et al. [15]. Henceforth, with the ''intuitive interfaces'' is referred to the complete system, including both the handheld interface and the robotic system that facilitates the use of alternative interfaces to steer conventional endoscopes.

Flexible endoscopy requires both quick tip steering (lumen navigation) and precise targeting (instrument placement for e.g., taking biopsies). Previously mentioned studies showed that both tasks require different control algorithms, which in turn leads to a need for different interfaces [16, 17]. We compared the user performance when using a handheld controller with a touchpad interface and with a joystick interface to the conventional method. The touchpad is combined with a position control algorithm, which has particular advantages in precise movements. The joystick is combined with rate control, which is recommended for wide workspace tasks [16, 17]. A non-linear rate control algorithm was implemented that provides both precise movements and quick tip steering with a single joystick (Fig. 1).

The aim of this research is to determine if the robotic setup and used interfaces are able to provide efficient control of the tip of a flexible endoscope, in terms of time and tip trajectory.

Materials and methods

Participants

Fourteen novices, participants without a medical background and without experience in flexible endoscopy, were included. Novices were chosen to evaluate intuitiveness of the steering methods, since evaluation at the start of a learning curve prevents intrinsic bias to one of the steering methods. There were eight men and six women, with an average age of 28 ± 5 years. All participants were right-handed. None of the participants were frequent users of joysticks or touchpads.

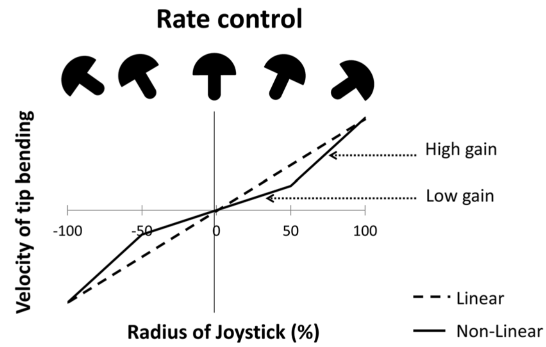

Fig. 1 A gain relates the joystick's position to the velocity of endoscope tip bending in the corresponding direction. The non-linear algorithm combines a low gain with a higher gain to create two zones, one with low and one with higher velocity changes

Setup

The simulated environment consists of a hollow tube with two rings of targets attached to the wall and on a circle inside the tube (Figs. 2, 3).

The distal ±15 cm of a standard flexible colonoscope (Exeria II CF-H180AL, Olympus, Tokyo, Japan) was inserted into this tube and fixated before the bending section to exclude shaft manipulation. A standard reusable biopsy grasper instrument (Olympus, Tokyo, Japan) was inserted through the working channel of the endoscope, protruding from the tip of the endoscope. A standard imaging unit (Exeria II CLV- 180, Olympus, Tokyo, Japan) was used to process the endoscopic images. Audio feedback informed the operator when a target was touched.

User interfaces

When using the conventional steering method, the user rotates two angulation wheels for up/down or left/right angulation. When using the alternative interfaces, an add-on robotic module actuates the angulation wheels. This module is connected to the conventional endoscope and positioned in a docking station as described by Ruiter et al. [15]. In this configuration, a feedback circle is visualized on-screen to inform the participant about the direction and the extent of tip bending (Fig. 3). The handheld controllers contain either a thumb joystick (model 802, P3 America, San Diego, USA) or a touchpad (Ergonomic touchpad, UK).

Control algorithms

The touchpad is combined with a position control algorithm, comparable to a laptop touchpad. When the user moves his/her thumb over the touchpad, the endoscope tip will bend in the corresponding direction. A faster thumb movement provides faster tip angulation. As the touchpad

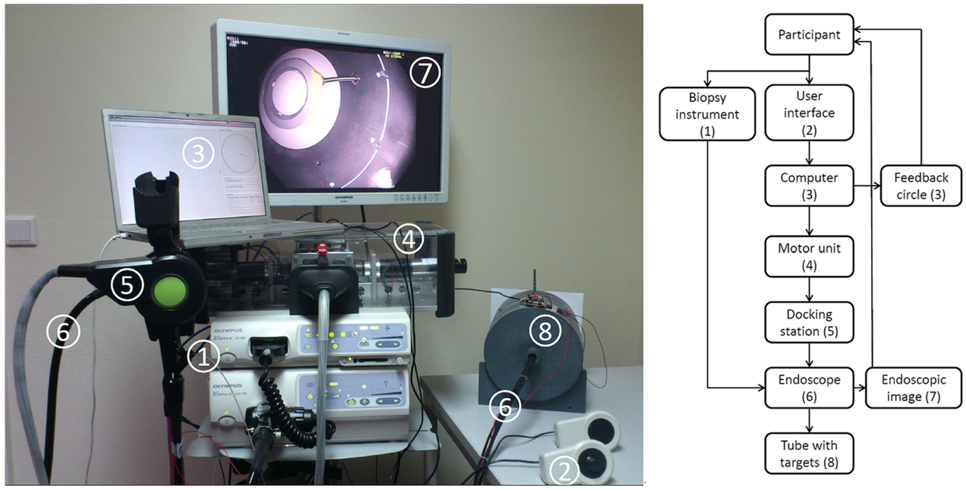

Fig. 2 Test setup and schematic workflow

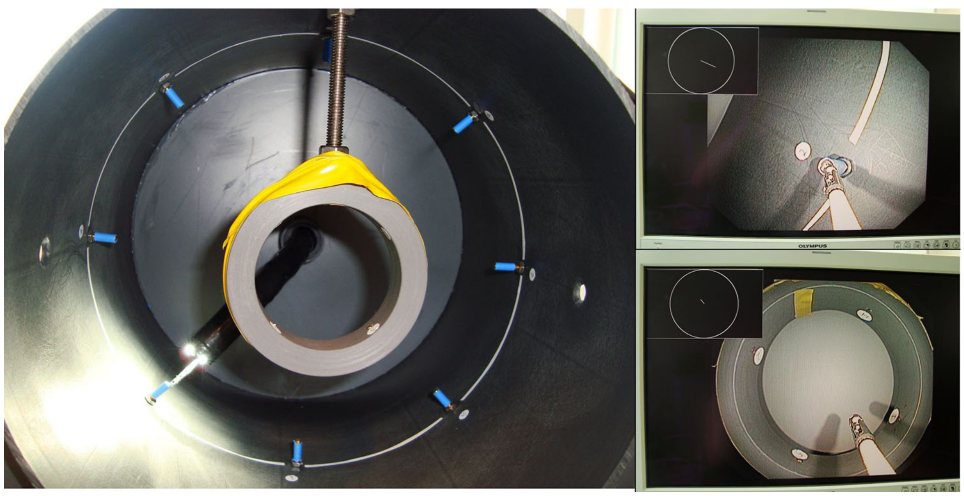

Fig. 3 (*Left*) The bendable distal part of the endoscope protrudes through a hollow tube with two rings of numbered targets. Touching the eight targets on the outer ring requires large endoscope tip movements, which represents the navigation task (task 1). The four targets on the inner ring are used for the small tip bending movements in the targeting task (task 2). The *upper right image* shows the endoscopic view of task 1, with a numbered target, guiding line to follow to the next target and *feedback circle* representing the amount and direction of tip bending. The *lower right image* shows the endoscopic view of task 2 with its feedback circle

surface is smaller than the bending range of the endoscope tip, repeated thumb motions are necessary to reach the full bending range (called clutching). The gain of the position control algorithm was adjusted to enable a single thumb movement on the touchpad to cover the small distance required for the targeting task (task 1). A higher gain would result in less clutching to cover the larger distance of task 2, though this inevitably results in less precision for small movements.

The joystick is combined with rate control. Rate control relates the position of the joystick to a velocity of tip bending in the corresponding direction. The user pushes the joystick in the required angulation direction. Pushing the joystick further from its neutral position will result in faster tip angulation. As the user can hold the joystick in a certain position, no clutching is required to reach maximal tip angulation. In linear rate control, a single gain factor relates the angular position of the joystick with the tip's angulation velocity. In non-linear rate control, two gains are combined to enable an area with low velocity and an area with higher velocity (Fig. 1). The low gain enables higher precision for small distances, while the high gain provides more efficiency in covering larger distances. A single gain (used in linear rate control) is a trade off between precision and speed. All gains were adjusted following a pre-experimental testing session.

Procedure

Participants were asked to steer the endoscope tip as quickly and fluently as possible to position it in front of eight targets. After positioning the tip, participants had to advance a grasper instrument through the working channel to contact the target. Two rings of numbered targets were located in the tube. To test navigational functionality, the first task was to touch 3-mm targets, equally distributed on a circle with a diameter of 200 mm. A line on the outer surface of the tube indicated the optimal path to the next target.

The second task simulated fine targeting functionality. Included were four targets of 1 mm on a circle with a diameter of 50 mm. Targets were placed such that horizontal, vertical, and diagonal movements were necessary. The size of the targets was adjusted to provide a similar index of difficulty as in the first task (defined by Fitt's Law as the ratio between path length and target size). To generate an equal number of measurements as in the first task, participants were asked to perform this task twice. They were asked to limit contact with the outer surface that represented the bowel wall.

Instruction and 5 min practice time were included before every task. Both tasks were performed once with each steering method: conventional, touchpad, linear joystick, and non-linear joystick. The order in which the steering methods were used was counterbalanced to prevent distortions due to learning effects or fatigue. The time between touching targets was electronically recorded, and the total time for each task calculated. Additionally, when using the intuitive interfaces, the motor rotations were registered by means of attached incremental optical encoders. Each encoder pulse relates to an endoscope tip angulation of $\sim 10^{-5}$ in that direction. Consequently, the number of motor pulses is related to the bending trajectory of the tip. This trajectory cannot be recorded for the conventional configuration.

Following the experiment, the participants were asked to select their preferred steering method for each task and with regard to their perception of control.

Statistical analysis

Statistical analysis was performed using IBM SPSS statistics version 21. Within-participant variances were calculated using Friedman's ANOVA for non-parametric data, followed by Wilkoxon's signed rank test as a post hoc test. The parametric data were analyzed using one-way repeated measures ANOVA with Tukey's LSD correction as the post hoc test [18]. p values under 0.05 were considered statistically significant. Bonferroni corrections were automatically applied. Values are expressed as median with interquartile range (IQR).

Results

The conventional steering method (266, 207–367 s) was significantly slower compared to all intuitive interfaces, when navigating over larger distances (task 1). Also, participants were significantly faster when using the touchpad (153, 116-184 s) compared to the linear joystick (185,154–309 s). There was no significant difference between using the touchpad and the non-linear joystick (148, 132–221 s) (Table 1; Fig. 4A).

When controlling small movements (task 2), participants were significantly faster using the touchpad (207, 165–234 s) and the non-linear joystick (222, 160–241 s) compared to the conventional method (244, 210–286 s) (Fig. 4B). Also, using the touchpad was significantly faster compared to the linear joystick (240, 203–262 s). There was no significant difference between using the touchpad and the non-linear joystick.

Using the non-linear joystick resulted in significant shorter tip trajectories, compared to using the touchpad (task 1: $p = 0.022$, task 2: $p = 0.008$) and linear joystick (task 1: $p = 0.024$, task 2: $p = 0.009$) (Table 1; Fig. 5).

The majority of participants preferred the non-linear joystick over the other control methods of steering the endoscope tip in large (7 out 14) and small (8 out 14) bending ranges. There was no significant difference in the user's preference between steering modules with regard to the perception of control.

Discussion

The aim of this study was to determine if the robotic setup with intuitive user interfaces is able to provide more efficient control of the tip of a flexible endoscope. The experiment shows that intuitive interfaces can reduce the time needed to position the endoscope tip compared to the conventional angulation wheels. Between the intuitive interfaces, the joystick with non-linear rate control showed a reduced tip positioning time, the shortest tip trajectory and scored highest in users' preference.

The used simulated environment is a strong simplification of clinical practice, where physicians use additional endoscopic maneuvers (e.g., shaft rotation) and the bowel wall response to suction and inflation. We will address these factors as a whole when endoscope manipulation will be evaluated in following experiments. The simple tubular structure currently used enabled objective and cross-subject evaluation of the focus of this study: tip steering only.

Flexible endoscopy requires both quick tip steering (task 1) and precise targeting (task 2). This experiment confirms that a touchpad combined with position control is quicker

Table 1 Total time and covered distance, presented as the median (IQR). The preference rate is the number of participants who preferred the specific controller for each tasks and related to the perception of being in control

	Conventional	Touchpad	Linear joystick	Non-linear joystick
Total time (s)				
Task 1	266 (207–367)	153 (116–184)*, **	185 (154–309)*	148 (132–221)*
Task 2	244 (210–286)	207 (165–234)*,**	240 (203–262)	222 (160–241)*
Total covered distance (sum of tip angulation) (°)				
Task 1	NA	1992 (1606–2334)	1882 (1551–2678)	1606 (1367–1884)†
Task 2	NA	1534 (1324–1821)	1540 (1332–1806)	1243 (997–1373)†
Preference rate				
Task 1	0	4	3	7
Task 2	3	2	1	8
Control	5	3	3	3

* Significantly faster compared to conventional for $p < 0.05$

** Significantly faster compared to linear joystick for $p < 0.05$

† Significantly shorter covered distance compared to both touchpad and linear joystick for $p < 0.05$

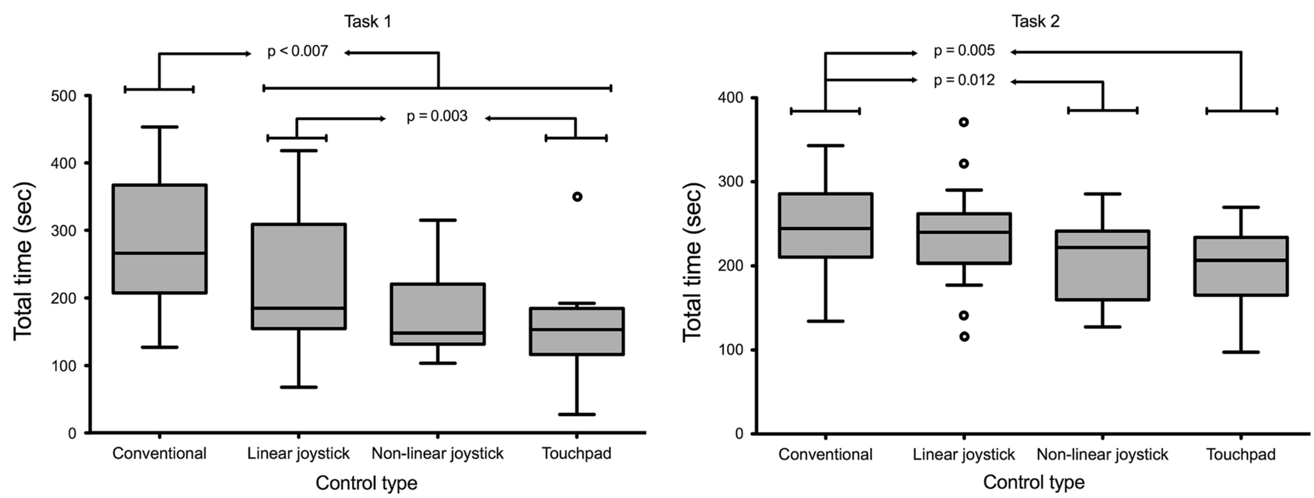

Fig. 4 Box-and-whisker diagrams representing the median and spread of time taken to perform the first (*left*) and second (*right*) task, per controller, with significance levels. The *spheres* represent results from outliers

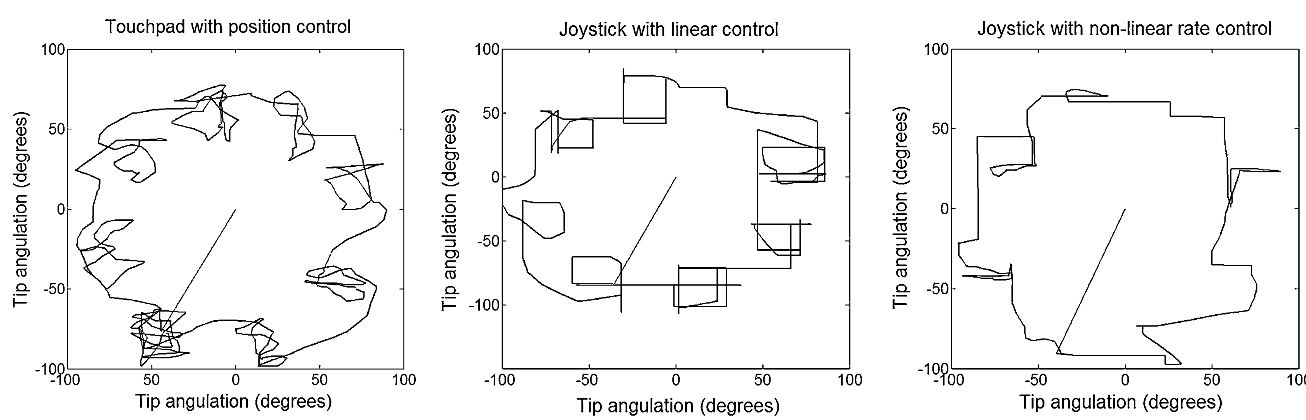

Fig. 5 Example of the endoscope tip trajectory by one participant performing task 1, using the touchpad (*left*) linear joystick (*center*) and non-linear joystick (*right*). Illustrated is the tip trajectory from center to targets 1–8 and back to 1

compared to a joystick combined with (linear) rate control, when performing a small targeting task (task 2).

The fast result for the touchpad in the large navigation task (task 1) was unexpected, since clutching induces additional thumb movements and, therefore, potentially causes increased path length and time [16]. Tip trajectory analysis showed a significant increase in path length, but no increase in time. The paths in this experiment could have been too short to induce clutching-induced time increase.

Apart from clutching, the tip trajectory is also affected by the responsiveness of the endoscope tip. Previous studies have shown that cable-driven flexible endoscopes generate significant hysteresis, which reduces control accuracy [19]. We noticed that participants suffered from over- and understeering when using the intuitive interfaces because they experienced difficulty in estimating the tip's response. These unnecessary tip motions could be harmful for the patient, particularly when instruments are protruding from the endoscope tip. When using the conventional control method, direct haptic feedback of the tension on the angulation wheels informs the user of the tip response. Haptic feedback is not yet available on the remote controllers. Instead, users are provided with the feedback circle to inform them about the tip's angulation. Since the participants considered visual feedback a poor substitute for haptic feedback, we will study alternative feedback methods.

We were able to show increased efficiency of endoscope tip positioning when using intuitive user interfaces. Also, we introduced a non-linear rate control algorithm that improved both time and tip trajectory. Based on these results, we will proceed to investigate alternative user feedback options, and continue our evaluations on in vitro anatomical models, and later in vivo experiments performed by experienced endoscopists.

Disclosure E. Rozeboom, J. Ruiter, M. Franken, and I. Broeders have no conflicts of interest or financial ties to disclose.

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