J Robotic Surg (2014) 8:319–324
DOI 10.1007/s11701-014-0473-0

ORIGINAL ARTICLE

Single-handed controller reduces the workload of flexible endoscopy

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Received: 26 March 2014 / Accepted: 27 May 2014 / Published online: 24 June 2014

Abstract The control of the conventional flexible endoscope is non-ergonomic and non-intuitive. A novel single-handed interface could reduce the experienced workload, without reducing current efficiency or effectiveness of endoscope manipulation. The aim of this study is to evaluate the workload, efficiency and effectiveness of a single-handed controller in colonoscopy, in comparison to a bimanual controller and the conventional angulation wheels. Twenty-one inexperienced students performed colonoscopies on a computer simulator using either the single-handed controller with a joystick interface, a bimanual controller with a joystick interface or the conventional angulation wheels. Participants performed three sessions of colonoscopies. After each session, the experienced workload was evaluated using a seven-component absolute scoring scale. Efficiency of the procedure was evaluated by the cecal intubation time and total-used scope length. Effectiveness was evaluated by the percentage of bowel wall visualization. The total workload of the single-handed controller was lower compared to the conventional angulation wheels for all three sessions. The total workload of the bimanual controller was lower compared to the conventional angulation wheels in the second and third session and also lower compared to the single-handed controller in the third session. There was no significant difference between the three control interfaces in time efficiency, used scope length or visualization performance. Single-handed and bimanual controllers with a joystick interface are a feasible approach to reduce the workload of colonoscopy without reducing efficiency or effectiveness of endoscope manipulation.

Keywords Flexible endoscopy · Single-handed · Joystick · Workload · Feasibility

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Introduction

The colonoscope is a flexible video-endoscope used to visualize the lumen of the large bowel. A colonoscope consists of a long flexible shaft with a camera mounted on the steerable tip (Fig. 1). The colonoscope is advanced through the flexible and tortuous large bowel by combining right-handed shaft manipulation (translation and rotation) with left-handed tip actuation (up/down and left/right angulation) and actuation of the suction and air/water inflation valves [1]. Alternatively, bimanual control is applied on the angulation wheels, while an assistant holds

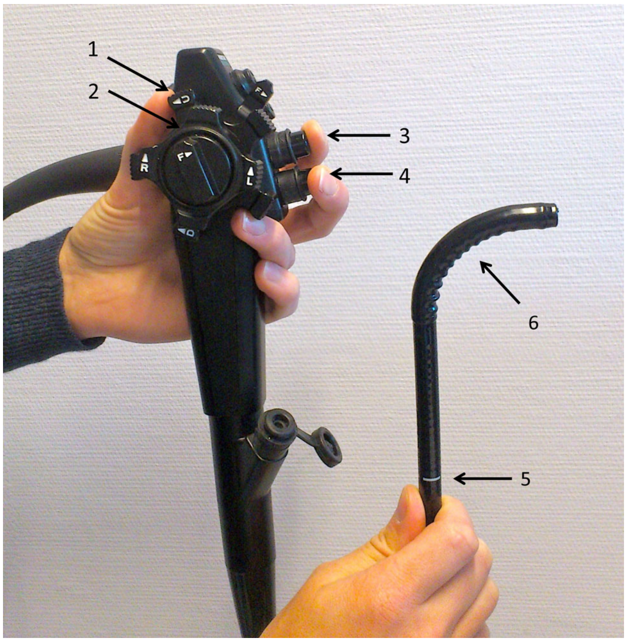

Fig. 1 Conventional single-person endoscope control. The endoscopist holds the control body in his left hand, controlling the up/down (*1*), left/right (*2*) angulation wheels, suction (*3*) and air/water inflation valves (*4*). The right hand controls the endoscope shaft (*5*) with the distal bendable tip (*6*)

the endoscope shaft. This 60-year-old control method is not perfect. Tip actuation is not very intuitive; the angulation wheels rotate in one plane, whereas the tip bends in two perpendicular directions. Furthermore, bimanual coordination of one instrument requires complex motor skills, especially when both hands perform different tasks, outphase and in different directions [2]. It takes on average 275 procedures to learn the motor skills to adequately perform colonoscopy [3, 4]. Secondly, the non-ergonomic design of the endoscope is associated with musculoskeletal complaints and injuries, with a prevalence ranging from 37 to 89 % amongst endoscopists [5].

The mental and physical load on the endoscopists will grow in the coming years. Population-based screening programs increase the demand for colonoscopy, which is currently the 'gold standard' for early detection and removal of adenomatous polyps, the precursors of colorectal cancer [6–8]. This growing demand will probably increase the endoscopic workload of current gastroenterologists, because of volume and growing complexity of endoscopic surgical interventions. It is a known fact that an inverse correlation exists between a physician's workload and the quality of healthcare [9]. Also, a higher rate of physical injuries can be expected, associated with a reduced endoscopic capacity and lower return of educational investments.

Robotics have the potential to reduce the experienced workload, because they enable the combination of different degrees of freedom in one intuitive and ergonomic hand-held control interface [10]. Robotics have already proven to reduce the mental and physical workload of bimanual manipulation tasks in laparoscopic and endoscopic procedures [11–13]. This paper describes the design of a single-handed controller with a joystick interface, which is developed to reduce the experienced workload of flexible endoscopy procedures. The workload, efficiency and effectiveness of the single-handed controller and the conventional angulation wheels are compared. A bimanual controller with joystick is included to separate the influence of single-handed vs. bimanual endoscope control from the influence of a joystick as a substitute for the angulation wheels.

Materials and methods

Design considerations

Design considerations were collected from interviewing seven experienced endoscopists and a workflow analysis of current procedures at the Meander Medical Centre (Amersfoort, The Netherlands) and the Ziekenhuisgroep Twente (Almelo and Hengelo, The Netherlands). Functional requirements include simultaneous control of the degrees of freedom of the endoscope shaft (intubation/withdrawal and rotation), tip angulation (left/right, up/down and combined directions) and functions like suction, air/water inflation and photo actuation.

Single-handed controller

The single-handed controller consists of an 'over the shaft' grip with a thumb-actuated joystick (model 802, P3

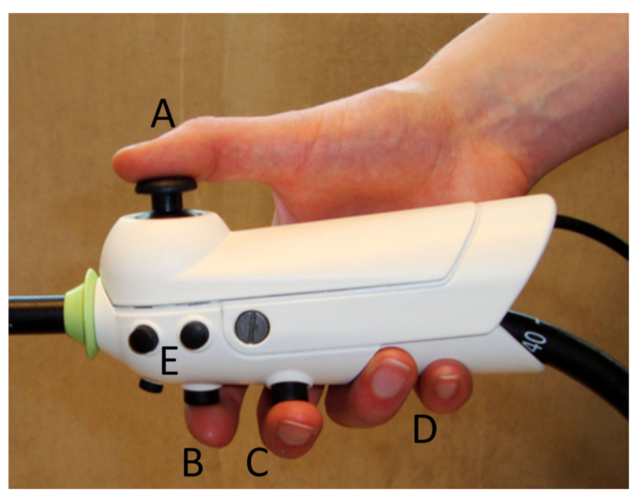

Fig. 2 The single-handed controller, with: *A* a thumb joystick, *B* air & water injection button, *C* suction button, *D* spring-actuated release handle and *E* three programmable buttons, e.g. for taking pictures

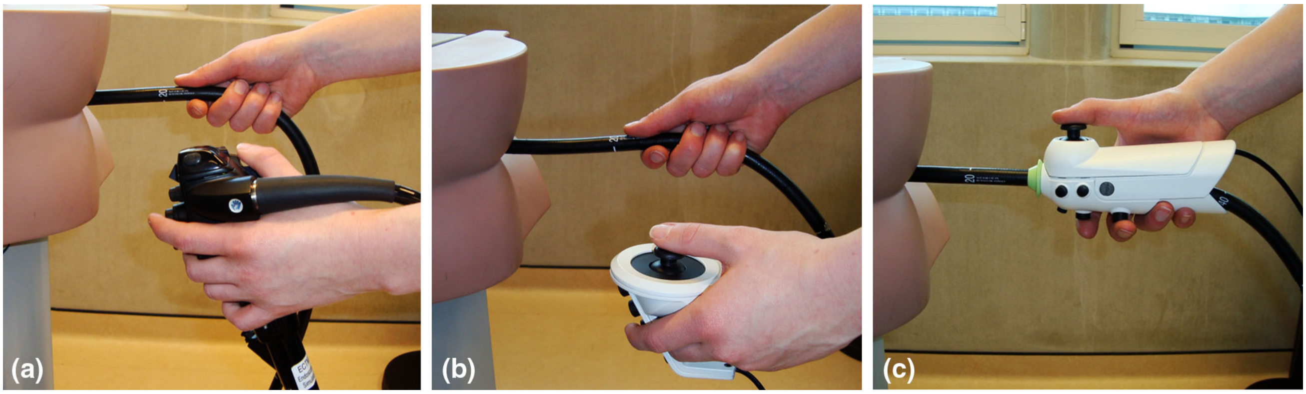

Fig. 3 Test configurations. Each group of participants used either the conventional (**a**), bimanual joystick (**b**) or single-handed joystick (**c**)

America, San Diego, USA) (Fig. 2). This grip allows the user to manipulate the endoscopic shaft and steer the tip with one hand (Fig. 3). The index finger actuates air inflation and lens rinsing functions, which are, similar to conventional control, combined in one button. A proportional sensor is used to differentiate between these two functions based on the amount of force exerted by the finger. The third finger actuates the suction button, allowing simultaneous inflation and suction without hand repositioning. The heights and positions of the buttons are chosen such that an ergonomic grip is provided and unintended actuation is prevented. The last two fingers release the spring actuated clamping mechanism to translate or rotate the controller over the endoscopic shaft. Three programmable buttons are included for frequently used functions, which can be operated by the thumb or index finger without releasing the controller.

Bimanual controller

The bimanual controller with joystick interface was included to separate the influence of single-handed vs. bimanual endoscope control, when using the joystick as a substitute for the conventional angulation wheels. Similar to conventional control, users combine right-handed shaft manipulation with left-handed tip actuation (Fig. 3). The tip is actuated using the remote controller with thumb joystick (same as single-handed controller) from Ruiter et al. [13]. Air inflation, lens rinsing and suction functions are actuated by the index and third finger, similar to the single-handed controller and conventional setup.

Conventional control

Conventional control was tested using a replica of a standard colonoscope (AccuTouch, CAE Healthcare, Montreal, QC, Canada; previously Immersion Medical, Gaithersburg, MD, USA). Users applied the single-person endoscope steering principle, described in the introduction (Figs. 1, 3).

Setup

All colonoscopies were carried out on the AccuTouch virtual reality endoscopy simulator (CAE Healthcare, Montreal, QC, Canada). The system consists of real-time computer graphics, an interface device with force-feedback on the endoscope shaft and audible response indicating patient discomfort. We used case 1 of the 'Introduction to Colonoscopy' module. Case 1 allows N-loop formation in the sigmoid, though this is not necessarily the case.

When using the bimanual or single-handed controllers, control information (tip angulation, suction and air/water inflation) was sent to the simulator through a computer connection. In practice, the computer sends control information to a motor unit, which in turn actuates the endoscopic functions [13]. In this study, the motor unit was omitted to allow a direct connection between computer and simulator, since the simulator requires electronic signals, instead of actual air and water suction/inflation. The control body of the conventional endoscope was placed in a mobile holding standard which allowed translation and shaft rotation (Fig. 4). A feedback diagram informed the users of the tip's angulation position and the steering direction necessary to straighten the tip [13].

Participants and procedure

Twenty-one students of Technical Medicine were included.[1] These participants had sufficient knowledge to understand the medical risks and consequences of a colonoscopy exam, though without previous experience in

[1] Technical Medicine is a Master's programme at the University of Twente (The Netherlands) where students integrate advanced technologies with medical sciences to improve patient care.

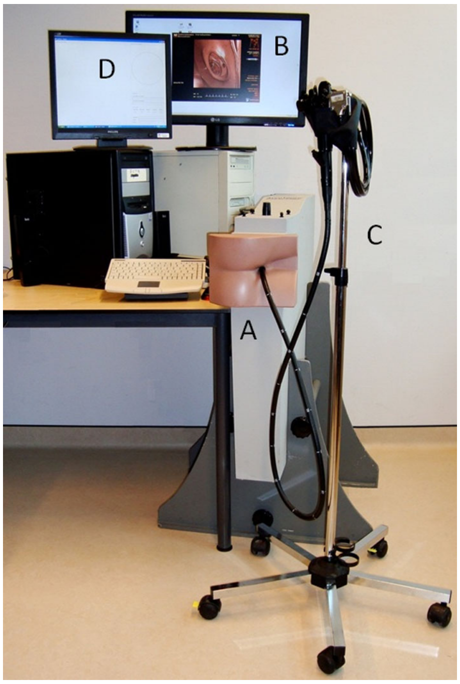

Fig. 4 Experiment setup, with *A* the virtual endoscopic computer simulator, *B* endoscopic image, *C* holding standard (when using bimanual and single-handed joystick interfaces) and *D* a screen with feedback diagram

endoscopy. The participants, 8 men and 13 women, age 22 ± 1 years, were randomly divided into three groups. Each group performed colonoscopies on a computer simulator using one of the three control interfaces: the conventional angulation wheels, the bimanual controller with joystick interface or the single-handed controller with joystick interface (Fig. 3).

Participants performed three colonoscopies over a period of 3 weeks. They were asked to introduce the endoscope into the cecum as fast as possible, without causing excessive patient pain, and visualize as much of the bowel wall as possible during withdrawal of the endoscope. Six minutes withdrawal time was advised, to conform current colonic polyp screening guidelines [14]. Before each testing session, participants were allowed to practice for 30 min during which they were informed on loop detection and straightening techniques. They were allowed to use the 'external view' option to verify the scope's position and shape in the simulated bowel. This information was not available during the testing sessions.

Evaluation parameters

Participants scored their experienced workload after each testing session, using an absolute scoring scale. They were asked to score seven statements on a scale of 1–5, with 1 representing a low workload and 5 representing a high workload. The statements are based on the six categories of the NASA Task Load Index, which includes the experienced mental, physical and temporal demand, performance, effort and frustration levels [15]. A seventh category is added to evaluate the anticipated endurance level. The participant scores if s/he expects to be able to perform the procedure during a whole working day. A sum of the workload scores represents the total experienced workload. The lowest possible total workload is 7; the highest possible workload is 35.

The participant's progress in efficiency was evaluated by two parameters; the time to reach complete intubation (cecal intubation time, s) and the total used scope length (cm). Effectiveness of the procedure was evaluated by the percentage of visualized bowel wall, computed by the computer simulator.

Statistical analysis

Data was analysed using IBM SPSS Statistics v.21 (2012). Curtosis and skewness *z*-scores were used to determine if the distributions are normal. Non-parametric, between group, differences were assessed using a Kruskal–Wallis test with Mann–Whitney as post hoc test. Pearson's correlation coefficient or Kendall's tau were used to evaluate correlation between parameters. A simple linear regression was used to evaluate learning curves between control interfaces. Values are expressed as the median with interquartile range (IQR). p values under 0.05 were considered significant.

Results

None of the participants caused a perforation. One student was excluded from the experiment because she was not able to reach the cecum with the single-handed controller. Evaluation revealed that this student did not encounter loop formation during the training session, and was unable to straighten the scope when looping occurred during the test.

The total workload of the single-handed control interface was scored significantly lower compared to the conventional angulation wheels for all three sessions ($p = 0.004$, 0.019 and 0.025) (Table 1; Fig. 5). The workload of the bimanual control interface reduced over the three sessions, with Pearson's correlation $r = -0.18$. The workload of the bimanual control interface was not significantly different from the other interfaces in the first session. The bimanual controller scored lower workload compared to the conventional control interface in the second session ($p = 0.001$). In the third session, the bimanual controller scored lower compared to both the conventional ($p = 0.002$) and single-handed interfaces ($p = 0.023$).

Table 1 Group performance per session and per control interface, expressed as median (IQR) of the total workload, efficiency and effectiveness scores

Control interface	Session 1	Session 2	Session 3
Total workload			
Conventional	22 (17–23)	19 (17–22)	18 (16–21)
Bimanual	17 (16–21)	12 (11–14)[a]	9 (8–11)[a,b]
Single-handed	14 (12–15)[a]	15 (13–17)[a]	15 (11–16)[a]
Intubation time (s)			
Conventional	271 (256–369)	180 (157–189)	136 (122–214)
Bimanual	289 (196–307)	198 (140–316)	155 (99–188)
Single-handed	324 (215–442)	169 (132–313)	114 (79–139)
Used endoscope length (cm)			
Conventional	399 (284–496)	299 (261–367)	276 (265–330)
Bimanual	418 (310–525)	295 (260–371)	280 (268–307)
Single-handed	343 (290–502)	276 (251–363)	265 (246–296)
Visualization performance (%)			
Conventional	97 (96–98)	97 (97–97)	97 (97–98)
Bimanual	97 (97–97)	97 (96–98)	97 (96–97)
Single-handed	97 (91–97)	97 (97–97)	97 (97–98)

[a] Significant difference with conventional angulation wheels

[b] Significant difference with single-handed control interface

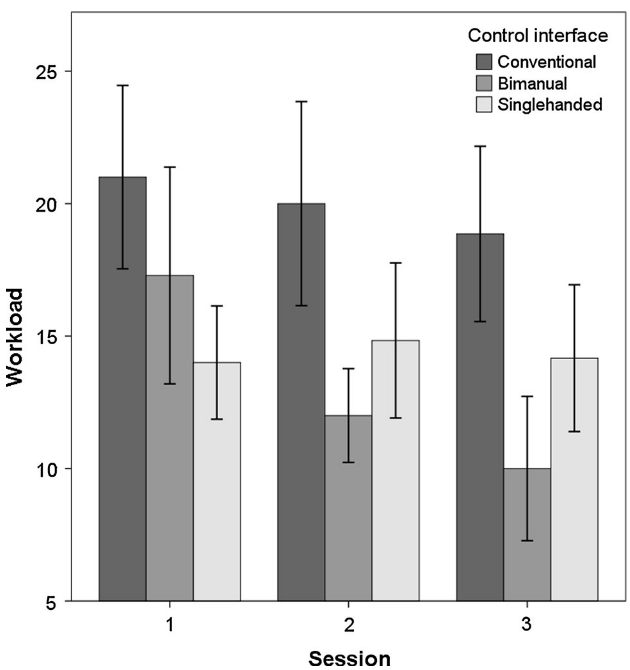

Fig. 5 Total workload scores per control interface per session with 95 % confidence interval

All groups showed significant reduction in both intubation time and used scope length, over the three testing sessions. Overall, the intubation time reduced from 310 (±190) s in the first session to 150 (±90) s in the last session, for all control interfaces. There was no correlation between the individual total workload scores and the intubation time. The total used scope length reduced from 370 (±120) cm in the first session to 276 (±30) cm in the last session. There were no significant differences between the three control interfaces in time efficiency or used scope length. The visualization performance of all participants was with an average of 97 (±1) % not significantly different between the sessions and between the control interfaces.

Discussion

We introduced a controller that enables single-handed control of both the endoscopic shaft and tip angulation. We showed that this controller with joystick interface is a feasible alternative for the conventional angulation wheels in simulated colonoscopy. The controller reduces the workload of endoscope manipulation while maintaining current efficiency and effectiveness of the procedure.

Using the workload components of the NASA TLX, albeit in a simple scoring scale, allowed us to add the anticipated endurance level and provided a quick and simple impression on the experienced workload for each group. Objective efficiency and effectiveness parameters were added to complete the evaluation of feasibility.

A previous study by Kuperij et al. [16] showed that replacing the angulation wheels by an ergonomic single-handed 'over the shaft' steering principle increases intuitiveness in shaft manipulation in simulated colonoscopy. However, the design suffered from sensor drift and high pressure on the pivoting point, making it unsuitable for clinical practice. Nevertheless, the study introduced two important design requirements: a adequate clamping without damaging the scope and easy release of the shaft in order to allow quick repositioning of the controller.

Preliminary studies by Ruiter et al. [13] and Rozeboom et al. [17] showed that bimanual joystick interfaces allow endoscopic tip positioning with reduced workload and reduced tip trajectory. A single-handed controller is expected to further reduce the experienced workload, since it creates the illusion that the endoscope is an elongation of the right arm. This configuration could enable easier 'torque steering', a combination of tip angulation, rotation and insertion, which is used to 'corkscrew' the endoscope through the flexible sigmoid [1]. Single-handed actuation of this 'corkscrew' motion was considered less complex, compared to bimanual manipulation [2].

However, this study did not show a persistent reduction in workload scoring for all sessions or in intubation efficiency compared to the bimanual controller with joystick interface. On the contrary, the bimanual workload was lower compared to the single-handed workload in the third session. During the experiments, we noticed that participants in the single-handed group steered the endoscope tip and shaft consecutively, not simultaneously. Assumingly, they consider the endoscope shaft and endoscope tip as separate systems, making bimanual control a more logical option than single-handed control.

The current repositioning method of the single-handed controller over the shaft might cause the experienced separation of endoscopic shaft and tip steering. Some participants required hand repositioning or left hand assistance to release the clamping mechanism, interrupting the scope manipulation process. An easier and lighter repositioning mechanism should allow continuous single-handed endoscope manipulation and the evaluation of the potential of single-handed endoscope manipulation. This may further reduce the experienced workload of endoscope manipulation.

The single-handed controller introduces a second benefit in endoscopic procedures; it frees the left hand to manipulate instruments like biopsy graspers or snares. Currently, the physician's right hand switches between endoscopic shaft and instrument manipulation, lacking constant control of all degrees of freedom. Using a single-handed controller in the intervention phase relieves the left hand to manipulate the instrument, enabling constant control of all degrees of freedom. A combination of single-handed and bimanual control configurations seems favourable. Wherein, bimanual control benefits manipulation to position the endoscope throughout the bowel and single-handed control could benefit the intervention phase.

Our next step is to design a control interface that enables the advantages of both these configurations. We will continue our work on optimizing the design features, followed by expert evaluations in a clinical setting.

Conclusion

Single-handed and bimanual controllers with a joystick interface are a feasible approach to reduce the workload of colonoscopy without reducing efficiency or effectiveness of endoscope manipulation. A combination of bimanual and single-handed configurations in one controller seems favourable in future.

Acknowledgments The authors wish to thank the Departments of Gastrointestinal Endoscopy of the Meander Medical Centre (Amersfoort, The Netherlands) and Ziekenhuisgroep Twente (Hengelo and Almelo) for their clinical input and DEMCON Advanced Mechatronics (Enschede, The Netherlands) for their technical support.

Conflict of interest E. Rozeboom, Dr. Ir. J. Ruiter, Dr. Ir. M. Franken, M.D. M. Schwartz, Prof. Dr. Ir. S. Stramigioli and Prof. M.D. I. Broeders declare that they have no conflict of interest.

Informed consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

1. Williams CB (2009) Insertion technique. In: Waye JD, Rex DK, Williams CB (eds) Colonoscopy: principles and practice, 2nd edn. Blackwell Publishing Ltd., London, pp 537–559
2. Swinnen S, Wenderoth N (2004) Two hands, one brain: cognitive neuroscience of bimanual skill. Trends Cogn Sci 8(1):18–25
3. Lee S, Chung I, Kim S, Kim J, Ko B, Hwangbo Y, Kim W, Park D, Lee S, Park C, Baek I, Park S, Ji J, Jang B, Jeen Y, Shin J, Byeon J, Eun C, Han D (2008) An adequate level of training for technical competence in screening and diagnostic colonoscopy: a prospective multicenter evaluation of the learning curve. Gastrointest Endosc 67(4):683–689
4. Sedlack RE (2011) Training to competency in colonoscopy: assessing and defining competency standards. Gastrointest Endosc 74(2):355–366
5. Shergill A, McQuaid K, Rempel D (2009) Ergonomics and GI endoscopy. Gastrointest Endosc 70(1):145–153
6. Seeff LC, Richards TB, Shapiro JA, Nadel MR, Manninen DL, Given LS, Dong FB, Winges LD, McKenna MT (2004) How many endoscopies are performed for colorectal cancer screening? Results from CDC's survey of endoscopic capacity. Gastroenterology 127(6):1670–1677
7. van Turenhout ST, Terhaar sive Droste JS, Meijer GA, Masclée AA, Mulder CJJ (2012) Anticipating implementation of colorectal cancer screening in The Netherlands: a nation wide survey on endoscopic supply and demand. BMC Cancer 12(1):46
8. Butterly L, Olenec C, Goodrich M, Carney P, Dietrich A (2007) Colonoscopy demand and capacity in New Hampshire. Am J Prev Med 32(1):25–31
9. Wallace JE, Lemaire JB, Ghali WA (2009) Review physician wellness: a missing quality indicator. Lancet 374:1714–1721
10. Klibansky D, Rothstein RI (2012) Robotics in endoscopy. Curr Opin Gastroenterol 28(5):477–482
11. Stefanidis D, Wang F, Korndorffer JR, Dunne JB, Scott DJ (2010) Robotic assistance improves intracorporeal suturing performance and safety in the operating room while decreasing operator workload. Surg Endosc 24(2):377–382
12. Hubert N, Gilles M, Desbrosses K, Meyer JP, Felblinger J, Hubert J (2013) Ergonomic assessment of the surgeon's physical workload during standard and robotic assisted laparoscopic procedures. Int J Med Robot Comput Assist Surg 9:142–147
13. Ruiter JG, Rozeboom ED, Van der Voort MC, Bonnema GM, Broeders IA (2012) Design and evaluation of robotic steering of a flexible endoscope. In: Proceedings of the IEEE international conference on biomedical robotics and biomechatronics
14. Rex DK, Petrini JL, Baron TH, Chak A, Cohen J, Deal SE, Hoffman B, Jacobson BC, Mergener K, Petersen BT, a Safdi M, Faigel DO, Pike IM (2006) ASGE quality indicators for colonoscopy. Gastrointest Endosc 63(4 Suppl):S16–S28
15. Hart SG, California MF, Staveland LE (1988) Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. Adv Psychol 52:139–183
16. Kuperij N, Reilink R, Schwartz M, Misra S, Stramigioli S, Broeders I (2011) Design of a user interface for intuitive colonoscope control. In: Proceedings of the IEEE/RSJ international conference on intelligent robots and systems (IROS), pp 937–942
17. Rozeboom ED, Ruiter JG, Franken M, Broeders IA (2014) Intuitive user interfaces increase efficiency in endoscope tip control. Surg Endosc [Epub ahead of print]