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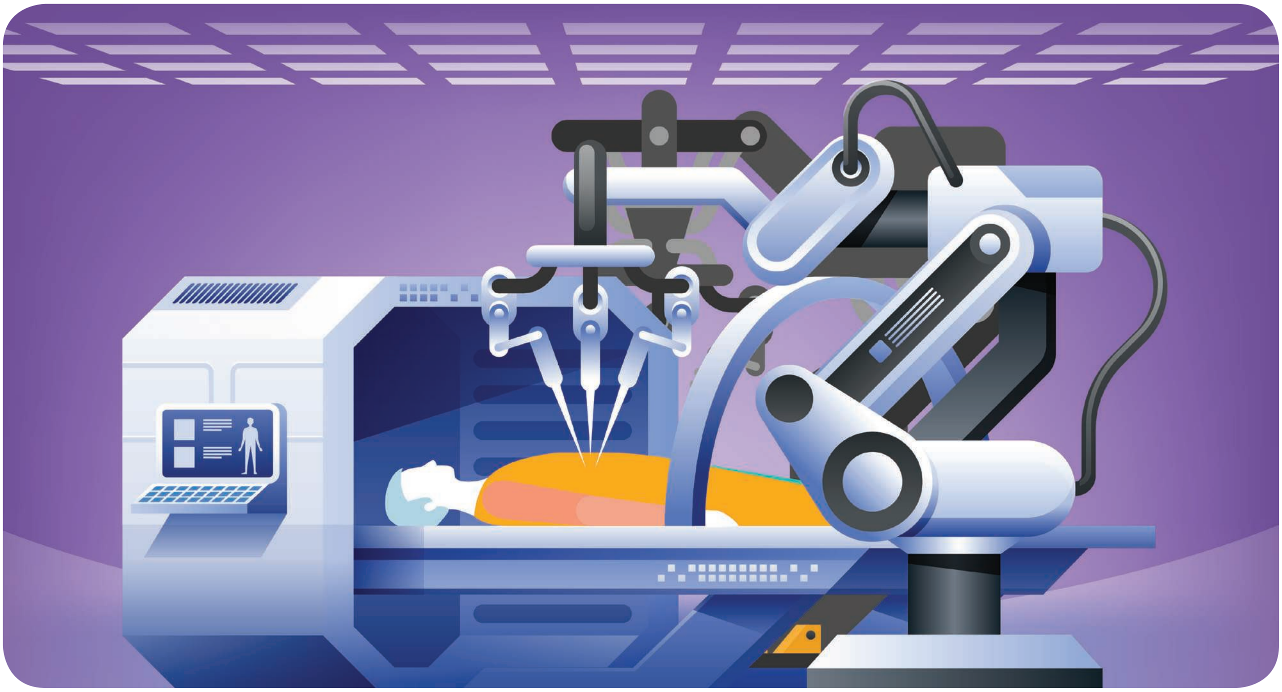
A Study on the Dexterity of Surgical Robotic Tools in a Highly Immersive Virtual Environment



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Assessing Usability and Efficacy

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Robot-assisted minimally invasive surgery (RAMIS) has produced noticeable benefits for patients in the recent years [1], making it a favorable approach for a wide range of surgeries. The benefits of improving the dexterity of patient side manipulators to enable surgeons to perform more complex tasks are offset by the increased complexity of teleoperation and cognitive and physical effort on the operator side typically. A right balance between higher dexterity and intuitive control in teleoperation is yet to be defined. In this study, a dexterous, anthropomorphic primary master controller was deployed to assess and compare the efficiency of simulated anthropomorphic surgical instruments in an immersive surgical concept. Virtual surgical training tasks were built using a gaming software engine (Unity) and performed using simulated surgical tools with extended degrees of freedom (DoF) in the surgical shaft and gripper and compared with

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the standard da Vinci (DV) grasper. The motion of the tools were controlled using commercial inertial measurement unit (IMU) sensor-based devices attached to the user's arms and hands. This article summarizes results obtained from three studies with similar features but different levels of complexity, taken with both lay users with no experience in surgery or teleoperation and surgeons experienced in RAMIS. The results showed that more than 70% of users achieved better results using articulated tools but required more physical and mental effort for teleoperation.

Introduction

Minimally invasive surgery (MIS) and its noticeable benefits for patients in terms of fast recovery makes it a popular choice for a wide range of surgeries. Open surgery has always been invasive, causing high stress and pain for the patient, a prolonged recovery and exposure to higher risks of infections [1]. MIS, on the other hand, requires small incisions to allow instrument shafts to enter the surgical site through trocars plus additional holes to insert lights and cameras. The small incisions cause less postoperative pain and leave smaller scars with overall better physical and psychological recovery [1], [2]. Even though benefits for the patient have been established, MIS brings some challenges to the operator, including vision, dexterity, and ergonomy [3].

RAMIS has overcome several identified MIS issues, such as fulcrum effect, surgeon's physical tremor due to muscular fatigue, and hand-eye coordination. These improvements have made some types of surgery, previously impossible, routinely performed in hospitals [4]. Robotic surgeries are widely used but come with high costs to the system, a lack of haptic feedback, and a steep learning curve for junior surgeons. The DV EndoWrist, with its three-axis joint resembling the dexterity of the human wrist, allows surgeons to perform dexterous tasks, otherwise difficult with rigid laparoscopic tools [5]. Laparoscopy has seen the addition of an elbow joint to secure surgical triangulation and positioning of the tools in single-incision laparoscopic surgery [6], [7]. Despite the progress made using rigid instruments with dexterous wrists in particular tasks, [8], there is continued demand for dexterity-motivated developments of more articulated tools. The number of DoF with more articulated and flexible tools as in [9] and [10], and a number of different research platforms for flexible access surgery have recently been developed, including highly articulated robotic probes [11], the multitasking platform [12], and two-module soft endoscopes [13] as well as other instruments for surgeries performed in particularly constrained areas, such as the throat [14]. However, increased the dexterity of the surgical tools increases teleoperation complexity. With a provision of increased instrument articulation, a more sophisticated primary controller is needed to meet the high number of DoF, as in [13].

High-DoF Master Controllers

In spite of some efforts to gain intuitive control of complex devices [15], [16], the difficulties associated with teleoperation are still impediments to the deployment of effective and usable dexterous secondary instruments. Examples of anthropomorphic control of robotic arms and optimized human–robot arm/hand mapping can be found in [17] and [18] using Kinect sensors and deep neural networks, respectively. Wearable approaches of arm/hand tracking based on commercially available sensors (Xsens products) [19], [20], although not developed specifically for surgeries, implemented the idea of using human body motion to control human-like robotic arms.

In the Horizon 2020 SMart weArable Robotic Teleoperated Surgery (SMARTsurg) project [21], funded by the European Commission, we explored how to enable more complex minimally invasive surgical operations by developing a wearable primary concept to reduce cognitive load by allowing greater teleoperation dexterity. In this direction, we conducted a large requirement-elicitation study with a group of surgeons from different surgical backgrounds [22], which highlighted potential benefits of the surgical wearable primary concept. For this purpose, we set up three user studies with the aim to assess advantages and limitations of an intuitive, anthropomorphic teleoperation system in simulated surgical scenarios. We investigated the efficacy of tools with an extended number of DoF, mapped and teleoperated by a commercial anthropomorphic tracking device.

Purpose

The purpose of this study was to evaluate dexterous, surgical robotic platforms adaptable to arm/hand anthropomorphic master controllers using a set of wearable sensors to control a high degree of dexterity patient side manipulators in immersive, virtual surgical environments. The instruments used in the simulations feature a different number of joints on the instrument shaft and various types of the surgical end effector.

Materials and Methods

We performed three user studies of increasing complexity on diverse occasions with three different user groups. In each study, different surgical instruments or primary control systems were used to execute the same set of tasks. All the virtual surgical tasks were built in Unity, a software for game design and graphic applications. Two different end effectors were tested: the DV standard grasper and the three-fingered tool (3 F), an anthropomorphic grasper proposed and developed in the SMARTsurg project. The length of the DV grasper is 28 mm. The 3 F tool has three articulated digits, each with two DoF. The first and second phalanx of each digit is 24.64- and 19.84-mm long, respectively. The 3 F tool is designed to have a powerful grasp and permit more dexterous manipulations. The surgical tasks were inspired by the DV training simulator, which features different single or bimanual tasks, including peg transfer, suturing, and so on. The virtual surgical tasks, aimed at testing instrument dexterity, intuitiveness, and ease of the primary controller, were co-designed with a surgeon experienced in using the DV surgical system. The tasks were not designed to be overly complex as the tests were performed both by expert surgeons and lay users with no previous experience in teleoperation. For immersive vision inside the virtual surgical environment designed in Unity, we used an HTC Vive virtual reality (VR) headset. Control of the virtual surgical tool was enabled with IMU sensors placed on the hands and arms of the users, including HTC Vive trackers, Manus VR gloves, and an Xsens suit (Figure 1). After each trial, participants were asked to complete the system usability scale (SUS) and NASA-Task Load Index (TLX) questionnaire. The former is used to assess the overall usability of the system to perform the given task, while the latter provided scores of users' perceived workload during task completion. Finally, a user-experience form (UEF) collected users' subjective feedback. The robotic surgeons were recruited at Southmead Hospital in Bristol, United Kingdom. Their participation provided a comparison of the usability of the system with the existing surgical robotic platforms.

Figure 1. A participant wearing a VR headset; Xsense suit with IMUs sensors on the upper arms, forearms, and hands; and Manus VR gloves to control surgical virtual tools.

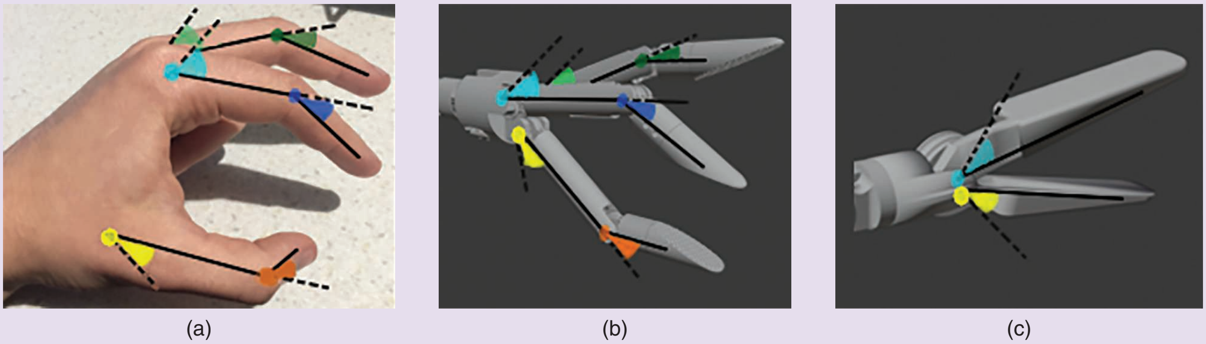
Patient Side Manipulator and Tool to Surgical Master Mapping

Posing of the tool shaft was controlled using a HTC Vive tracker placed on the participants' forearm, while the opening and closing of the end-effector tool was controlled with Manus VR gloves. We mapped metacarpophalangeal joints of the thumb and index finger to the virtual DV grasper joints (open/close). For the 3 F tool, we additionally mapped the proximal interphalangeal joint of the thumb, index, and middle fingers to the second joint of each digit of the 3 F tool (Figure 2). The details of the kinematic mapping to the DV tool are available in the calibration, and sampling of the Manus gloves are automatically managed by Manus' proprietary VR Apollo software. Users can simply open and close the DV grasper by opening and closing the hand. This is similar to the DV's primary controller (Figure 2). The motion of the articulated shaft was controlled with the IMU sensors of the Xsense, which were placed on the forearm, upper arm, and hands of the user. After calibrating the IMU sensors for each participant, the wrist joint (W) of the instrument was mapped to the user's wrist and the shaft of the instrument was mapped to the user's arm. A shaft with an elbow joint (E) was also tested, and it was mapped to the user's elbow. The joint values on the surgical tools were limited to their maximum physical values. The tool insertion velocity was calculated from the velocity of the user's arms in the forward direction and in respect to the global reference frame, taking into account the limitations of the fulcrum point, and scaling the tool velocity with a factor of 0.7 to maintain better tool control.

User Studies and Surgical Tasks

Articulated Tooltip Comparison (Surgical Task B.1)

The first user group was composed of 12 subjects, including two surgeons experienced in using the DV surgical robot. In the first trial, the surgical training task of grasping and positioning was performed with six squared colored rings, which were picked up and placed around color-coordinated pegs using one hand (Figure 3). In this task, we compared the



(a) (b) (c)

Figure 2. (a) Mapping of the finger joint angles to the 3 F and the (b) DV grasper. The DV primary only allows opening and closing of the (c) DV grasper.

dexterity of the two end effectors (DV and 3 F grasper) shown in Figure 2 while keeping the shaft of the instrument rigid.

Articulated Shaft Comparison (Surgical Task B.2)

The aim of this experiment was to compare the performance of instruments with rigid and articulated shafts while having the same type of the grasper (DV EndoWrist). The participants used a standard DV tool enhanced with a W with 3 rotational DoF, as in the DV EndoWrist. The instrument's shaft with an additional E placed at 3.75 cm from the tooltip along the shaft added an additional DoF to the shaft. The tasks in this study are the same as in the user study. Ten participants took part in this study, including one surgeon experienced in robotic surgery.

Dexterous Instruments Comparison (Surgical Task B.3)

We further investigated different combinations of shafts and graspers to carry out a more complex surgical task. Four different combinations of shafts and two grasper types (used in the first two studies) were compared: 1) a tool shaft with a W and DV grasper, 2) a tool shaft with a W and 3F grasper, 3) a tool shaft with an E and DV grasper, and 4) a tool shaft with E and 3F grasper. The task was to pick up colored objects and place them in the corresponding color boxes, with the right or the left hand, one at a time (Figure 4). The colored boxes were placed inside the cavities and behind tubular obstacles, which posed additional difficulty for moving and maneuvering the virtual surgical tools. The users were asked to complete the task four times, with each shaft/end-effector combination. In this trial, motion of the shafts was partially constrained, emulating trocar points inside the patient. Additionally, as in the real surgical system (DV robot, Intuitive Surgical, Inc.), we used a clutch to lock/unlock the tool motion to avoid uncomfortable upper-body and arm poses of participants. The clutch was controlled by a pedal. The study was performed 10 ten lay users with no previous experience in teleoperation and three surgeons experienced in using the DV surgical robot. For each trial, the time needed to complete the task and the number of collisions registered between the tools and the obstacles were recorded.

Results

Articulated Tooltip 1 Comparison

Performance

The time and velocity of each transfer were recorded, and the mean and standard deviation were computed for each subject. The mean time and velocity among participants were compared using the two tools. The results show a noticeable difference between the two-fingered DV grasper tool and the 3 F anthropomorphic grasper, both in terms of duration and speed of performing the task. For lay users, the mean transfer time was 2.6 ± 1.3 s and 3.4 ± 1.5 s when using the DV and 3 F graspers, respectively. For surgeons, the mean transfer time was 2.7 ± 1.6 s and 3.5 ± 1 s for the DV and 3 F graspers, respectively. The mean velocity for lay users was 8.7 ± 3.1 cm/s and 7.1 ± 2.6 cm/s for the DV and 3 F graspers, respectively. For surgeons, the mean speed was 9.1 ± 4.1 cm/s and 7 ± 2.5 cm/s for the DV and 3 F graspers, respectively (Figure 5). All the

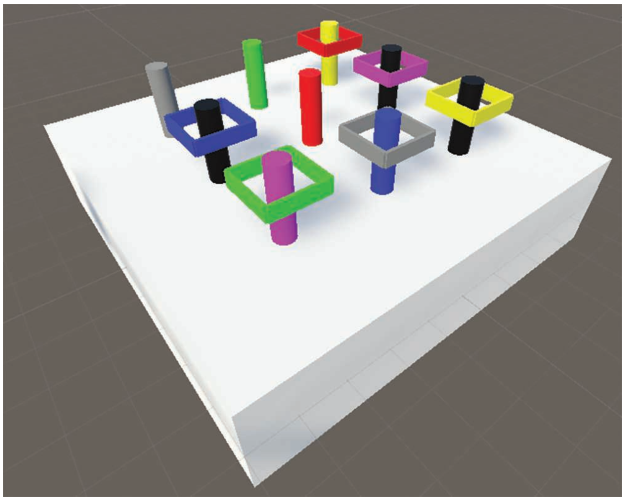


Figure 3. The virtual setup has six colored squares and nine colored pegs. The task is to move the squares to the same-color pegs.

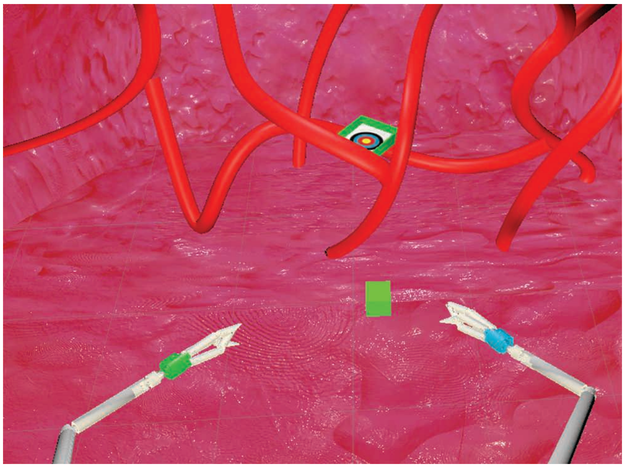


Figure 4. In the designed training, task users have to move colored boxes to the target platform behind the tubes using the correct instrument (in this case, left).

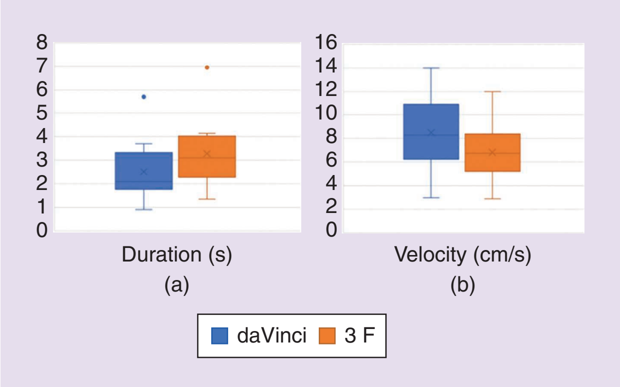


Figure 5. (a) The mean transfer duration and (b) velocity for surgical task B.1.

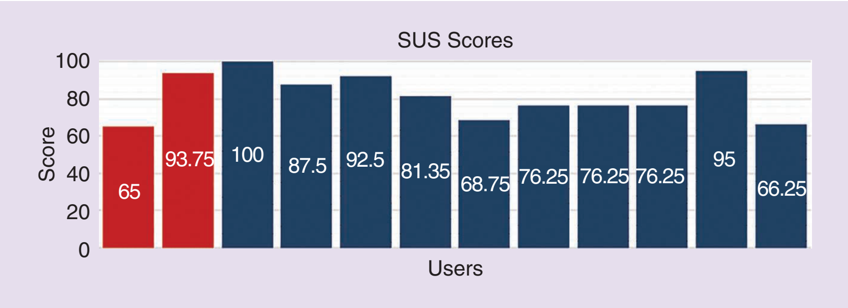


Figure 6. The SUS scores of lay users (blue) and surgeons (red) for surgical task B.1.

comparisons are statistically significant according to the Wilcoxon sign test, considering the results nonnormally distributed with $p < 0.05$. The 3 F grasper required slower movements to perform the same task when compared to the DV grasper. Moreover, the UEF demonstrated that the users had a preference for the DV tool for this type of pick-and-place task and that the 3 F grasper was deemed unnecessarily complex.

Questionnaires

The SUS results taken after the trials showed a median score of 78.8 and 79.4 for the lay users and experienced surgeons, respectively, demonstrating a similar ease of use of the two graspers (Figure 6). The NASA-TLX questionnaire (Figure 7) recorded median values of 19.8 and 27.3 for the lay participants using DV and 3 F, respectively, while for the surgeons, the median values were 10.6 and 22.3, indicating their ease of use of the DV grasper and a higher effort in using the more articulated grasper. Both sets of results have shown a statistically significant difference, with $p < 0.05$ demonstrating the DV grasper's advantage for performing pick-and-place tasks.

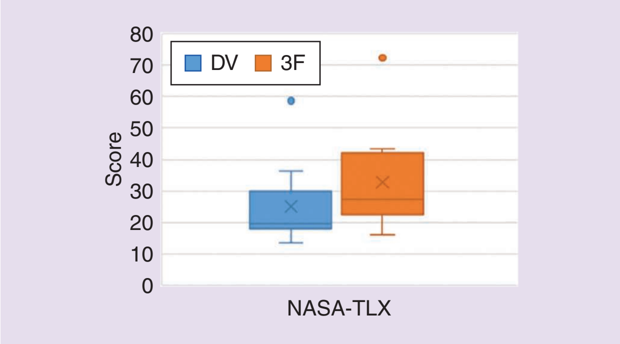
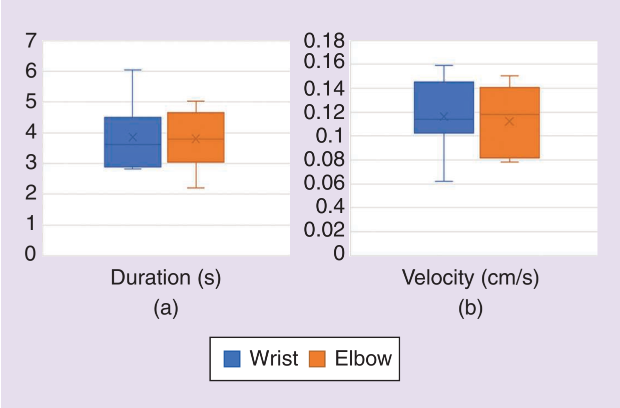


Figure 7. The NASA-TLX average scores for surgical task B.1.



(a)

(b)

Figure 8. (a) The mean transfer duration and (b) velocity for surgical task B.2.

Articulated Shaft Comparison

Performance

As before, the mean time and velocity among participants were compared using the two surgical tools. Both the duration of the task and speed of performance showed almost the same values between the two articulated instruments: the mean transfer time was 3.98 ± 1.12 s and 3.63 ± 1.15 s for the shaft with a W and the shaft with an additional E, respectively. The mean transfer velocity was 11.24 ± 3.4 cm/s for the W and 11.08 ± 3.49 cm/s for the E. The surgeons involved in the trials performed similarly, with a mean transfer time of 2.59 s and mean velocity of 16.69 cm/s (Figure 8). According to the Wilcoxon test, the performance differences between the two shafts are not statistically relevant.

Questionnaires

The SUS results showed a median value of 70 and 35 for the lay users and surgeon, respectively, (Figure 9). The lower usability scores recorded for the first experiment were likely due to the more extensive wearable kit required for control of the shaft but also because of the higher complexity of the articulated shaft's control. The NASA-TLX results demonstrated median values of 54.67 and 57 for the W and the E, respectively, for lay users, and 18.7 and 60.3, for the W and the E, respectively, as perceived by the surgeon (Figure 10). A lower workload was reported when using the shaft with only a W. As stated in the UEF, participants found moving the wrist to control the tool orientation relatively easy, but a few of them found it difficult to reach certain targets in a comfortable orientation when controlling the shaft with the E. In general, seven subjects out of 10, including the surgeon, preferred the W shaft configuration, finding the shaft with an elbow configuration unnecessary complex and harder to control for this type of task.

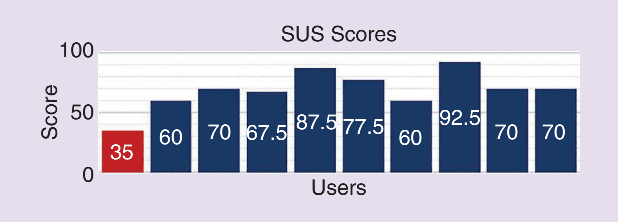


Figure 9. The SUS scores of lay users (blue) and surgeons (red) for surgical task B.2.

Dexterous Instruments Comparison (Surgical Task B.3)

Performance

In these trials, participants had to perform the more complex task of avoiding obstacles during pick-and-place tasks while using mechanisms that are closer to surgical reality, such as foot clutches to control tool movements. The participants adapted differently to the primary control with a broad performance range both in terms of the execution time and the number of collisions with the virtual anatomic structures, as presented in Figures 11 and 12 and Tables 1 and 2. For each user, we identified which of the four different shaft/grasper combinations achieved his/her best performance both in terms of the time needed to complete the task and the number of collisions with the virtual anatomical structures. Comparing the performance of a single user using four different tools, a lower number of collisions was achieved when using the elbowed tool. This was the case for five out of 10 lay users using the E 3 F, and for six out of 10 using the E DV. Some of them achieved the same score with multiple tools while only three of them achieved their best score using the W DV tool, and none of them did so using the W 3 F device. From these results, it appears that the E 3 F helped to avoid anatomical obstacles when compared to the use of a less dexterous tool by the same participant. The kinematic control of the two graspers was also compared, but there was no significant difference in using different graspers. Dexterity of the shaft affected performance more than end-effector dexterity (DV or 3 F). From the UEF it emerged that increased complexity of the tool shaft was often an obstacle to intuitive control, leading to increased control effort for half of the participants. The simpler tool was preferred by six out of 10 users, but for 40% of participants, the E felt more natural because it was similar to the human arm and consequently more intuitive. However, after a short learning period, it became apparent that most of the users could adapt quickly to the E shaft. Furthermore, the best performance (nine out of 10 users) was achieved in the second attempt when using either the W or E shaft, in any order of the task performance. The surgeons performed similarly to the lay participants, having experienced the same adaptation to the more dexterous patient side manipulators, different from the one they currently use on the Da Vinci robot.

Questionnaires

The SUS resulted in a median score of 63.75 and 57.5 for lay participants and surgeons, respectively (Figure 13). The results confirmed that the system was not immediately easy to use and required a short training time. These results differ from the first two trials and the simple pick-and-place scenario. The NASA-TLX questionnaire produced median scores of 46.33 for the E 3 F, 62.83 for the E DV, 62 for the W 3 F, and 59.83 for the W DV. For surgeons, the median score was of 62 for the E 3 F, 63 for the E DV, 32.3 for the W 3 F, and 56.67 for the W DV (Figure 14). The Wilcoxon test

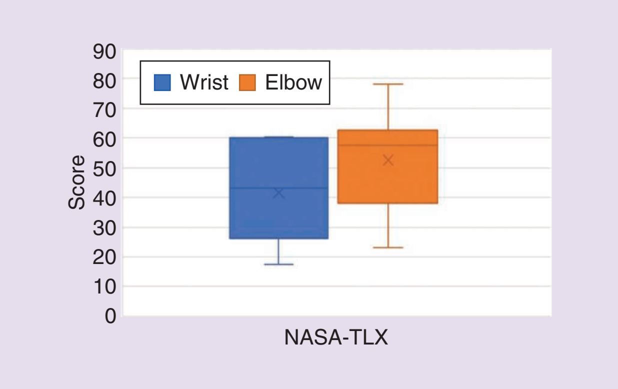


Figure 10. The NASA-TLX scores for surgical task B.2.

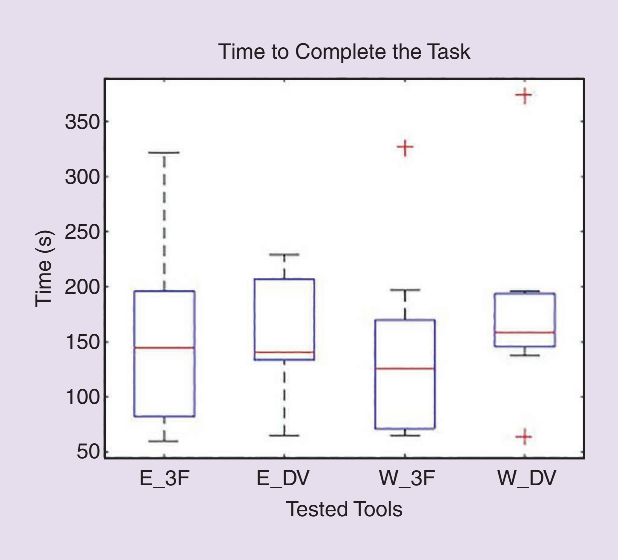


Figure 11. The task completion times for the four shaft/end-effector combinations in surgical task B.3.

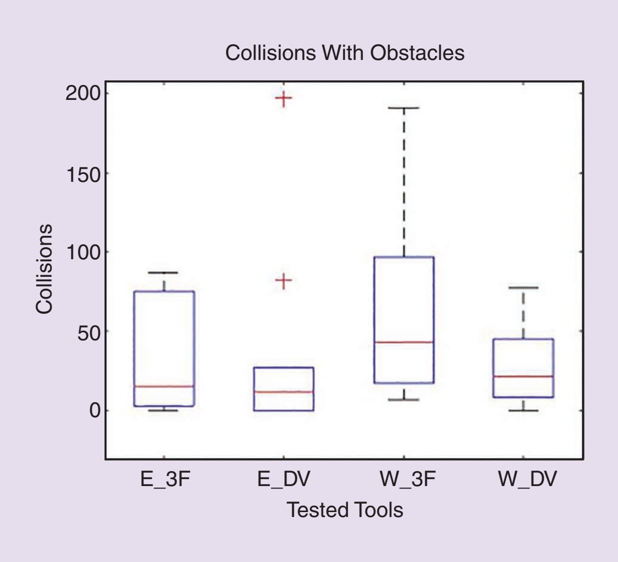


Figure 12. The number of shaft collisions with the virtual objects for the four shaft/end-effector combinations in surgical task B.3.

could not indicate a significant difference for one of the tested tools due to high standard deviations. These results, together with the UEF scores, highlight the need for a learning period for both lay participants and experienced surgeons when using more dexterous tools. There are strong indications that more dexterous tools facilitated better results in subsequent attempts when compared to a less dexterous DV instrument configuration.

Table 1. The average completion time in seconds.

Tools	W_DV	W_3F	E_DV	E_3F
Mean	176.8	139	154.3	151.4
Standard deviation	79	80.1	56.6	80.2

Table 2. The average number of collisions.

Tools	W_DV	W_3F	E_DV	E_3F
Mean	27.8	62	35.1	31.9
Standard deviation	25.8	52.7	62	80.2

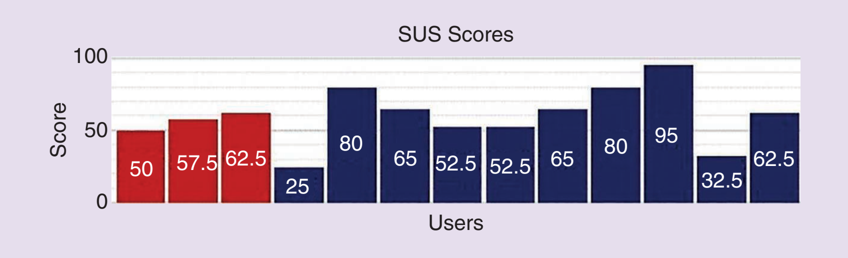


Figure 13. The SUS scores of lay users (blue) and surgeons (red) for surgical task B.3.

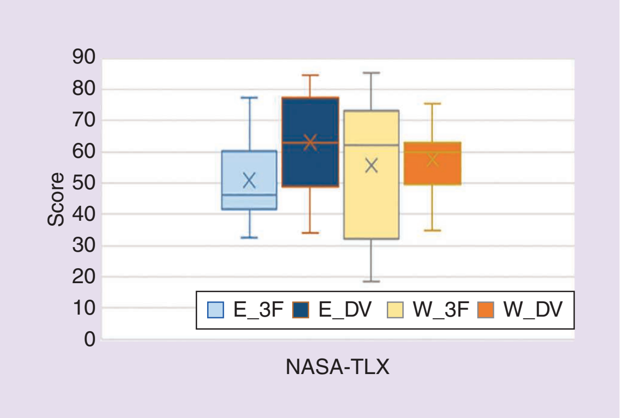


Figure 14. NASA scores for the four shaft/end-effector combinations when performing surgical task B.3.

Table 3. The surgeons' average scores.

	Time (s)			
Tools	**E_3F**	**E_DV**	**W_3F**	**W_DV**
Mean	149.68	196.51	172.04	215.52
Standard deviation	21.01	0	0	164.98

	Collisions			
Tools	**E_3F**	**E_DV**	**W_3F**	**W_DV**
Mean	42.5	48	81	114
Standard deviation	24.75	0	0	145.67

Conclusions and Future Work

The purpose of this work was to assess the usability and efficiency of an anthropomorphic, immersive teleoperation concept in a virtual, minimally invasive surgical environment to demonstrate the dexterity limits and teleoperation suitability in several small-scale user studies. From our preliminary set of trials, it was obvious that adding dexterity to the robotic surgical instruments does not necessarily reap benefits in terms of speed and efficiency when performing simple pick-and-place tasks. For the precision grasping task (surgical task B.1), the DV grasper was a better choice for most of our participants, while the 3 F grasper seemed only to add more mental workload and not enhance grasping efficacy. Similarly, the presence of the E on the shaft and the associated complexity of control did not provide any performance improvement in surgical task B.2 but facilitated better results with the more complex task (surgical task B.3), which included object avoidance and reaching behind virtual structures.

The SUS feedback from the first two trial groups showed that participants found the anthropomorphic primary control easy and intuitive to use, although unnecessarily complex. However, in the last set of trials (surgical task B.3), this approach proved to have an advantage over the lower dexterous shaft and grasper. After initial control difficulties in the first attempt mainly due to the constrained motion of the tools and use of the clutch, task performance improved in all subsequent attempts. The results shown in the "Dexterous Instruments Comparison (Surgical Task B.3)" section indicate that increased dexterity of the primary/secondary teleoperation can provide better efficiency for more complex tasks and potentially reduce training times for surgeons, while improving speed of movement and safety of the anatomical structures (Tables 1 and 2). A larger number of participants over a longer test period, primarily surgeons experienced in robotic surgery, would help achieve more statistically consistent results of this concept. As a future prospect, further co-development of the concept with surgeons experienced in robotic surgery would be useful to test this concept in more realistic simulations as well as on actual robotic systems, and to provide more insight into usability and learning curves. Realistic but not constraining haptic feedback can be added to improve the transparency and performance of surgical teleoperation.

Acknowledgments

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