Underwater Robotic Suturing

Running title: **Underwater Robotic Suturing**

Masahiko Kawaguchi, PhD; Masanari Shimada, PhD; Norihiko Ishikawa, PhD; Go Watanabe, PhD

Department of General and Cardiothoracic Surgery, Kanazawa University, Ishikawa, Japan

Correspondence:

Masahiko Kawaguchi, PhD

Department of Surgery, Yokohama Sakae Kyosai Hospital

132 Katsura-cho, Sakae-ward, Yokohama 247-8581, Japan

Tel: +81-45-891-2171; Fax: +81-45-895-8351

E-mail: surgkw@gmail.com

Abstract

Background: Laparoscopic and robotic surgeries have become popular, and this popularity is increasing. However, the environment in which such surgeries are performed is rarely discussed. Similar to arthrosurgery performed in water, artificial ascites could be a new environment for laparoscopic surgery. This study was performed to determine whether robotic surgery is applicable to complicated suturing underwater.

Material and Methods: A da Vinci Surgical System S was used. A weighted fabric sheet was placed at the bottom of a tank. Identical sets were made for each environment: one tank was dry, and the other was filled with water. The suturing task involved placement of a running silk suture around the perimeter of a small circle. The task was performed eight times in each environment. The task time and integrity score were determined. The integrity score was calculated by evaluating accuracy, tightness, thread damage, and uniformity; each factor was evaluated using a five-point scale.

Results: Although statistically significant differences were not shown in either the task time or integrity score between the underwater and air environments, robotic suturing underwater is not inferior to performance in air.

Conclusions: The feasibility of robotic suturing underwater was confirmed under the herein-described experimental conditions.

Keywords: Saline-filled surgery; ascites; robotic surgery; laparoscopic surgery; suturing

Introduction

Laparoscopic surgery has become extremely popular, and its popularity continues to increase (1). The devices, procedures, and anatomical knowledge used in laparoscopic surgery have greatly improved in recent years. However, the environment in which laparoscopic surgery is performed has received much less attention.

The environment in which a surgical procedure is performed is a fundamentally important factor. Laparoscopic surgery is usually performed in a gas-filled environment, and the most popular medium is carbon dioxide (CO_2) gas. The safety of CO_2 pneumoperitoneum has been established; however, CO_2 pneumoperitoneum is not a physiological condition, and its influences on the body have not been fully elucidated (2). Additionally, increased CO_2 consumption is not environmentally favorable from an ecological viewpoint.

Space exploration has recently been progressing. Longer stays in space require preparations for sufficient medical care (3). Thus, the ability to perform surgical procedures in space crafts or space stations is also required. Because of the limited volume within space crafts, CO_2 consumption during laparoscopic surgery should be avoided.

These issues raise the possibility of the use of space-occupying materials other than CO_2 gas for laparoscopic surgery. Liquid may be one such candidate material. Ascitic fluid is a physiological material, and its volume increases in some pathological conditions. Therefore, artificial ascites may be favorable for laparoscopic surgery. In the past, visual disturbances caused by bleeding prohibited the performance of underwater laparoscopic surgery. However, laparoscopic surgery now induces less bleeding because of the recent development of procedures and devices; thus, underwater laparoscopic surgery may be possible. In fact, experimental underwater laparoscopic cholecystectomy in a swine model has been reported (4), and we have reported saline-filled laparoscopic liver resection in a rabbit model (5). In the clinical setting, underwater endoscopic surgery is an established technique for transurethral resection of the prostate (6) and arthrosurgery (7). Therefore, the feasibility of underwater laparoscopic surgery should be further explored.

Robotic surgery, now available through the da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA, USA), was developed to overcome the drawbacks of laparoscopic surgery such as unsteadiness of the handheld camera and a limited degree of freedom when using forceps (8). Robotic surgical systems provide stable three-dimensional vision and precise movement of forceps with seven degrees of freedom using an anti-tremble filter. Additionally, such systems are available for telesurgery. Therefore, the performance of robotic surgery is expected to be superior to that of laparoscopic surgery in different environments.

However, because robotic surgery has specific benefits and drawbacks in different clinical situations, the indications for robotic surgery should be selective (9). Robotic surgery is useful for performance of meticulous procedures in fixed and narrow surgical fields such as the pelvic cavity, but is less useful in wide surgical fields (8).

The present study was conducted to evaluate the performance of underwater robotic surgery. A robotic suturing task was used for this purpose because suturing is one of the specific procedures made easier with robotic surgery in many cases (10,11).

Material and Methods

An experimental robotic suturing task was designed to evaluate the performance of underwater robotic surgery compared with robotic suturing performed in the usual air environment. Using a robotic surgical system, the suturing task was performed in two different environments: underwater and in air (control). Robotic performance was expected to be more difficult in the underwater environment than in the control environment.

The da Vinci Surgical System S, which contains three instrument arms, was installed onto the experimental equipment; a large needle driver was attached to the right arm, and a fenestrated forceps was attached to the left. A nonwoven fabric polyester sheet was used to cover a stainless wire tray, and the fabric sheet was marked for the suturing task as described below. The marked sheet was then weighted and placed in a tank without fixation to the bottom, allowing mobility and buoyancy during underwater surgery. Two identical sets were prepared (one for each environment); the tank for the underwater environment was filled with water (Figure 1).

An elaborate suturing task was designed to simulate reconstruction of a tube or tubular organ. The task involved ligation and placement of a running suture around a small circle (inner diameter, 10 mm; outer diameter, 15 mm) (Figure 2), which was dotted 16 times at even distances. The suture began and ended at the 3-o'clock position, progressing in the counterclockwise direction using 3-0 surgical silk (Ethicon, Inc., Somerville, NJ, USA) (Figure 3). The first stitch was ligated three times, and the 16th stitch was completed with an Aberdeen knot. This suturing task was intended for robotic surgery because it was deemed too difficult to perform using laparoscopic devices.

One surgeon certified in robotic surgery performed all tasks, both underwater and in air. After setting up the experimental model, the suturing task was practiced eight times before performing the study. The task was then randomly performed eight times in each environment. The order was a computer-generated list of a random set provided by an independent physician. All performances of the task were recorded with a video recorder.

The two outcome measures were time and integrity. Time was defined as the duration in seconds from placement of the first stitch to completion of the last tie. Integrity was evaluated using four factors: accuracy, tightness, thread damage, and uniformity. Each factor was evaluated using a five-point scale according to one person's subjective assessment (a laparoscopic surgeon blinded to the assignments). The overall integrity score was then determined by adding the scores of the four factors.

All values are presented as mean ± standard error. Student's t-test was used to compare the two surgical environments with respect to normally distributed variables. Differences were assessed using two-sided tests with an alpha level of 0.05. The analyses were performed using R 3.1.2 (R Foundation for Statistical Computing, Vienna, Austria).

Results

The main results of the study are shown in Figure 4. Although the difference was not statistically significant, the mean task time was shorter in the underwater environment (712 s) than in the control environment (780 s) ($p = 0.114$). Similarly, the mean integrity score was higher in the underwater environment (17.6) than in the control environment (15.9) ($p = 0.075$). Because neither the task time nor the integrity score was related to the order in which the task was performed, the learning curve did not influence the data. Therefore, performance of the robotic suturing task underwater was not inferior to its usual performance in air.

The details of the integrity score are shown in Figure 5. The redundancy score was significantly different between the two environments. Although the other scores showed no significant differences, the scores for all factors were higher underwater than in air.

Overall, these data suggest that the performance of robotic suturing underwater is not inferior to its ordinary performance in air.

Discussion

In this study, the performance of robotic suturing underwater was not inferior to that in air; in fact, our data suggest that it is superior. Robotic suturing has been confirmed to be beneficial for meticulous and precise reconstruction of tubular organs and has a rapid learning curve, and its performance time may be shorter than that of laparoscopic procedures (10,11). The present study revealed that the benefits of robotic suturing underwater are similar to those in air.

Despite some expected difficulties in the underwater environment, such as visual disturbances and difficulty of manipulation, robotic suturing underwater exhibited feasibility. In the present study, some aspects of underwater robotic manipulation were superior to those of standard robotic surgery. One potential contributor to this finding is the presence of water resistance, which may promote smooth hand and instrument motion. The underwater environment reduces the mechanical vibration of robotic arms during rapid motion. The stability of the three-dimensional camera in the robotic surgical system is one of its most beneficial features, and this stability is also an advantage when used underwater. A previous study confirmed that laparoscopic surgery can be performed in environments of minimal gravity (12). An underwater environment may provide similar conditions because the water buoyancy counteracts the effects of gravity.

The present experiment was performed by just one robotic surgeon. However, it was performed with randomization and blinded evaluation and adequately demonstrated the effectiveness of robotic suturing underwater compared with usual suturing in air. Additionally, water was used instead of saline, which is used for wet labs; however, the difference between water and saline is not expected to have a great impact on the suturing performance of laparoscopic surgery.

In vivo surgery performed underwater has many practical issues (13). The most important issue is the potential inability to adequately visualize bleeding. If the surgical field cannot be visualized, the surgical procedure cannot be performed. Previous experiments involving underwater surgery have shown that bleeding occurs in five patterns: droplet, streamer, cloud, pooling, and dispersion (13). Effective techniques for hemostasis and resolution of ascites are required. Additionally, complications associated with the viscera would be handled differently *in vivo* than in an experimental model. What physiological changes occur in association with artificial ascites? What effect does light refraction have on laparoscopic surgery *in vivo*? These issues must be resolved one by one. The present study represents the first step in the investigation of underwater robotic surgery.

The present study has shown the suturing performance of robotic surgery underwater. As described above, laparoscopic surgery underwater has some difficulties, such as a clear view without bleeding or floating viscera. These problems of underwater surgery are similar to those of surgery performed in low gravity (13). The recent development of energy devices has enabled less bleeding during surgery and the performance of experiments involving laparoscopic surgery underwater (4,5). However, such devices are not applicable to the performance of surgery in the clinical setting. Although laparoscopic or robotic surgery underwater cannot yet replace ordinary laparoscopic surgery, an experiment involving robotic arthrosurgery underwater has shown benefits of robotic surgery (14). Development of new devices and procedures is needed to establish the feasibility of robotic surgery underwater.

Acknowledgments

The da Vinci Surgical System S used in the present study was the property of Kanazawa University Hospital. This work was supported by JSPS KAKENHI Grant Number 23659642.

Disclosure of interests

Drs. Kawaguchi, Shimada, Ishikawa, and Watanabe report no financial interests or potential conflicts of interest. The authors alone are responsible for the content and writing of the paper.

References

1. Harrell AG, Heniford BT. Minimally invasive abdominal surgery: lux et veritas past, present, and future. Am J Surg 2005;190:239–43.
2. Brokelman WJA, Lensvelt M, Borel Rinkes IHM, Klinkenbijl JHG, Reijnen MMPJ. Peritoneal changes due to laparoscopic surgery. Surg Endosc 2011;25:1–9.
3. Beck G, Melton S, Dulchavsky SA. Critical care medicine in space. Aviat Space Environ Med 2005;76:163.
4. Igarashi T, Shimomura Y, Yamaguchi T, Kawahira H, Makino H, Yu W-W, et al. Water-filled laparoendoscopic surgery (WAFLES): feasibility study in porcine model. J Laparoendosc Adv Surg Tech A 2012;22:70–5.
5. Shimada M, Kawaguchi M, Ishikawa N, Watanabe G. Saline-filled laparoscopic surgery: A basic study on partial hepatectomy in a rabbit model. Minim Invasive Ther Allied Technol. 2014;26:1-8.
6. Van Hest P, D'Ancona F. Update in minimal invasive therapy in benign prostatic hyperplasia. Minerva Urol Nefrol 2009;61:257–68.
7. Katz JN, Gomoll AH. Advances in arthroscopic surgery: indications and outcomes. Curr Opin Rheumatol 2007;19:106–10.
8. Taylor GW, Jayne DG. Robotic applications in abdominal surgery : their limitations and future developments. Int J Med Robot 2007;3:3–9.
9. Maeso S, Reza M, Mayol JA, Blasco JA, Guerra M, Andradas E, et al. Efficacy of the Da Vinci surgical system in abdominal surgery compared with that of laparoscopy: a systematic review and meta-analysis. Ann Surg 2010;252:254–62.
10. Jayaraman S, Quan D, Al-Ghamdi I, El-Deen F, Schlachta CM. Does robotic assistance improve efficiency in performing complex minimally invasive surgical procedures? Surg Endosc 2010;24:584–8.

11. Passerotti CC, Passerotti AMAMS, Dall'Oglio MF, Leite KRM, Nunes RL V, Srougi M, et al. Comparing the quality of the suture anastomosis and the learning curves associated with performing open, freehand, and robotic-assisted laparoscopic pyeloplasty in a swine animal model. J Am Coll Surg 2009;208:576–86.
12. Panait L, Broderick T, Rafiq A, Speich J, Doarn CR, Merrell RC. Measurement of laparoscopic skills in microgravity anticipates the space surgeon. Am J Surg 2004;188:549–52.
13. Satava RM. Surgery in space. Phase I: Basic surgical principles in a simulated space environment. Surgery. 1988;103:633-7.
14. Bozkurt M, Apaydin N, Işik C, Bilgetekin YG, Acar HI, Elhan A. Robotic arthroscopic surgery: a new challenge in arthroscopic surgery Part-I: Robotic shoulder arthroscopy; a cadaveric feasibility study. Int J Med Robot 2011;7:496–500.

Figure legends

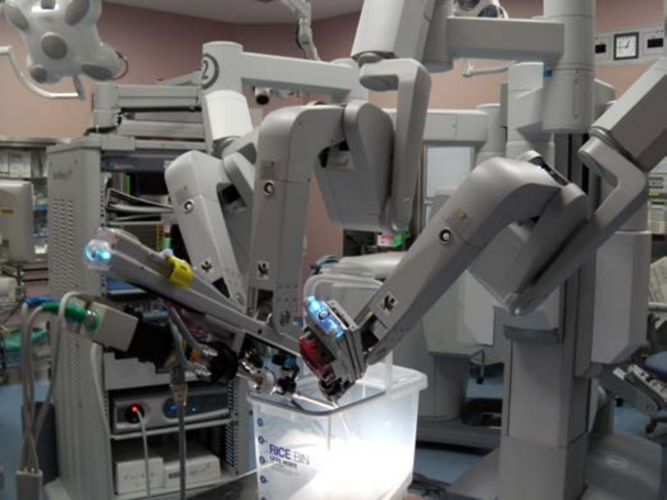
Figure 1. Experimental model. The da Vinci Surgical System S was installed onto the experimental equipment. The fabric sheet for suturing was set onto the bottom of a tank. For the water environment, the tank was filled with water.

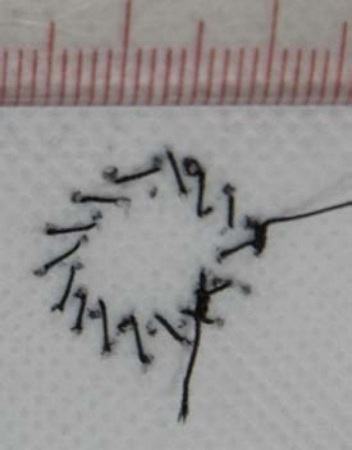
Figure 2. Suturing task. Nonwoven fabric polyester was used. Two circles (inner diameter, 10 mm; outer diameter, 15 mm) were marked on the fabric, with 16 points placed around the circle as a guide for suturing.

Figure 3. Suturing task in water environment. A running suture was placed in the counterclockwise direction.

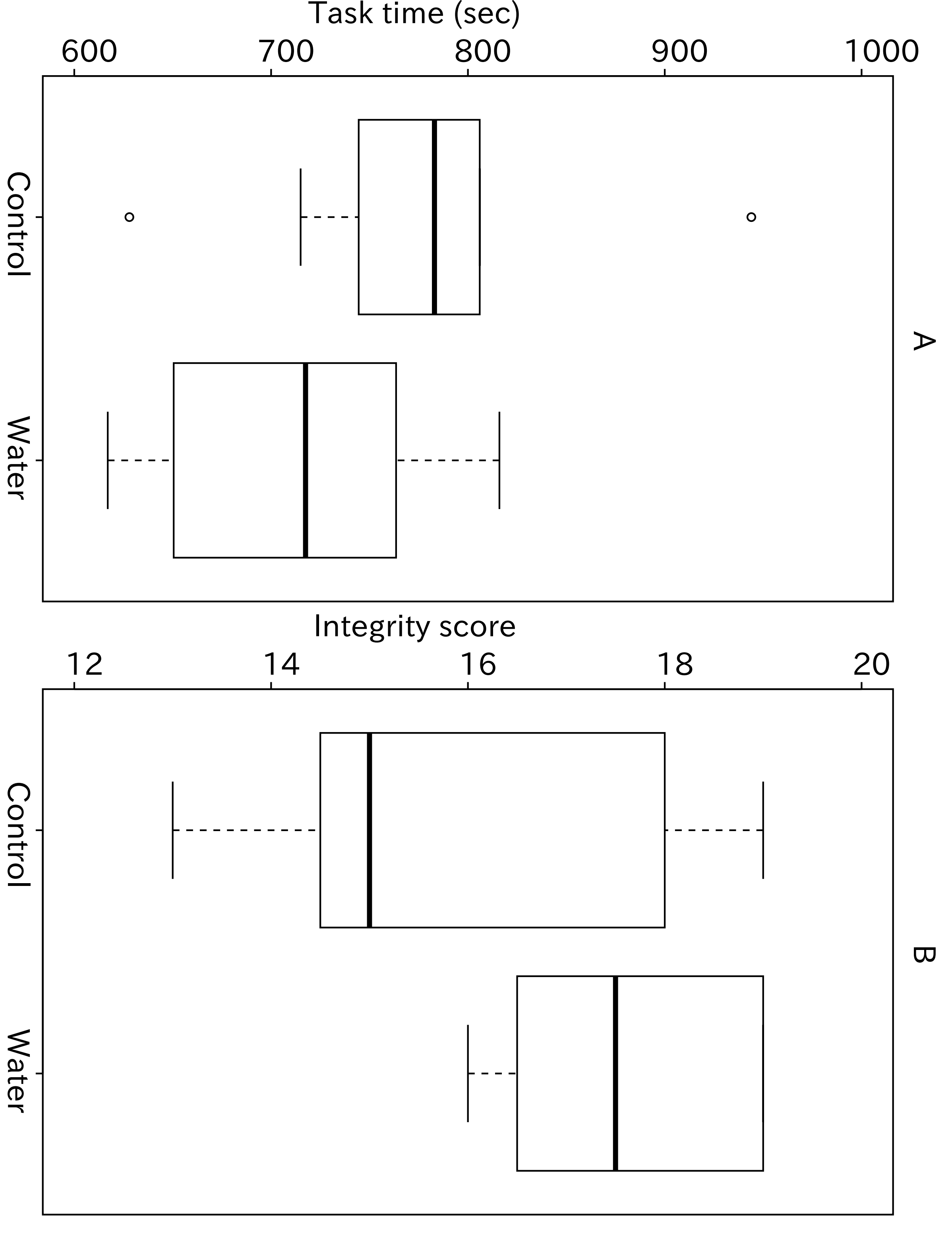
Figure 4. Outcome measures. (A) Task times in the two environments. **(B)** Integrity scores in the two environments. Although the mean time was shorter and the mean score was higher in the water environment, there were no statistically significant differences.

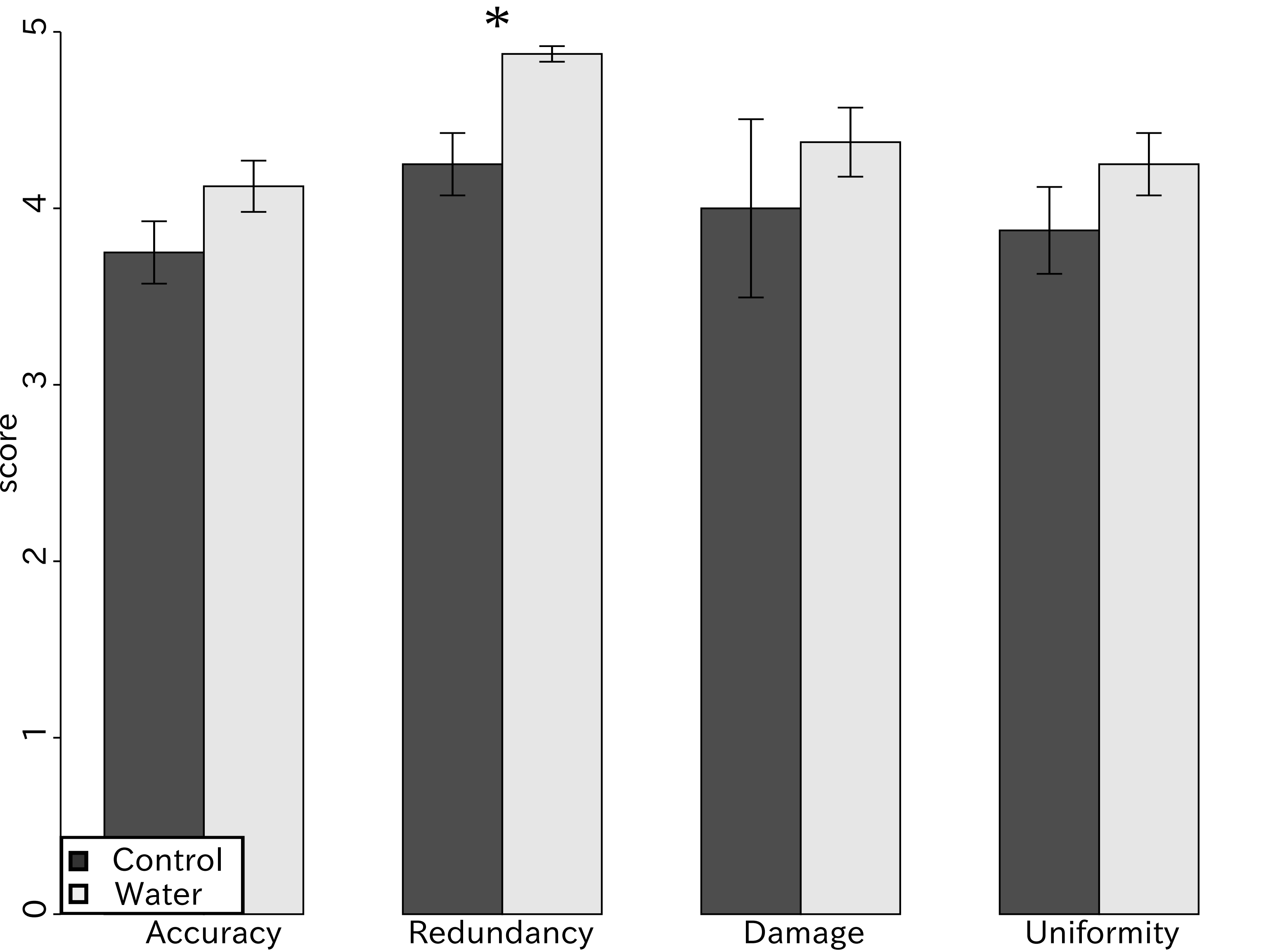
Figure 5. Mean score of each integrity factor. Data are shown as mean ± standard error. $*p < 0.05$


2
RICE BIN




2
1
4:3
TRAINING INSTRUMENT: NOT FOR HUMAN USE


Task time (sec)
600
700
800
900
1000
Control
Water
A
Integrity score
12
14
16
18
20
Control
Water
B



score
0
1
2
3
4
5
*
Control
Water
Accuracy
Redundancy
Damage
Uniformity