Surg Endosc (2018) 32:183–190
https://doi.org/10.1007/s00464-017-5655-1

Analysis of the posture pattern during robotic simulator tasks using an optical motion capture system

Kenta Takayasu[1] · Kenji Yoshida[1] · Takao Mishima[1] · Masato Watanabe[1] · Tadashi Matsuda[1] · Hidefumi Kinoshita[1]

Received: 8 March 2017 / Accepted: 6 June 2017 / Published online: 29 June 2017

Abstract

Background Surgeons are sometimes forced to maintain uncomfortable joint positions during robotic surgery despite the high degree of instrument maneuverability. This study aimed to use an optical motion capture system to analyze the differences in posture patterns during robotic simulator tasks between surgeons at two skill levels.

Methods Ten experienced and ten novice surgeons performed two tasks in a da Vinci Skills Simulator: Suture Sponge 1 (SP) and Tubes (TU). The participants' upper body motion during each task was captured, including the joint angles (axilla, elbow, and wrist), the percentage of time when the wrist height was lower than the elbow height (PTW), and the height of the elbow and wrist relative to the armrest.

Results The novice group showed significantly more excess extension in both elbow angles and extension (>50°) in both wrist angles than did the experienced group. The novice group had significantly lower PTW than the experienced group on the right side in both tasks (both $p < 0.001$), and on the left side in SP ($p < 0.001$). Compared with the experienced group, the novice group had a significantly higher elbow relative to the armrest on the right side (SP, TU: $p < 0.05$), and a significantly lower wrist relative to the armrest on the right side (SP, TU: $p < 0.05$).

Conclusions An optical motion capture system can detect the differences in posture patterns in the positional relationship between the elbow and wrist and the joint angles of the upper limb between two groups of surgeons at different skill levels during robotic simulator tasks.

Keywords Robotic surgery training · Motion capture system · Skill analysis

Robotic surgery has recently become popular in various surgical fields, due to its stereoscopic visualization, high degree of freedom regarding instrument movement, minimal invasiveness, and minimal bleeding in the operative field. Although the high degree of instrument maneuverability in robotic surgery reduces surgeon stress and muscle fatigue [1, 2], surgeons are also forced to maintain uncomfortable joint positions intraoperatively. Surgeons performing robotic surgery have a relatively large degree of physical symptoms or discomfort, similarly to those performing laparoscopic surgery [3–5]. The adoption of unnatural postures while conducting surgery might cause musculoskeletal complaints and decrease surgical performance.

The science of ergonomics for posture analysis was first discussed in the 1950s to create a comfortable work environment [6]. Optimal ergonomics to monitor position and instrument handle design have also been investigated to reduce surgeons' physical stress [7, 8]. Also, with recent progress in engineering technology, reports on minimally invasive surgery and gastrointestinal endoscopy have analyzed surgeons' motion using motion capture systems (electromagnetic systems, video-based analysis systems, inertial systems) during simulated tasks or actual surgery [9–13]. Adopting the proper posture could potentially prevent the excessive force that is sometimes accidentally applied by novice surgeons; therefore, this information is needed for surgical education.

✉ Hidefumi Kinoshita
kinoshih@hirakata.kmu.ac.jp

[1] Department of Urology and Andrology, Graduate School of Medicine, Kansai Medical University, 2-5-1 Shinmachi, Hirakata, Osaka 573-1191, Japan

There are some reports in robotic surgery on the frequency of musculoskeletal problems and the correlations between usage of the armrest and learning curves [14, 15]. However, there are no reports investigating the difference in posture patterns between surgeons at different skill levels. We hypothesized that the position pattern of joint angles and the positional relationship during robotic surgery differs depending on the skill level of the surgeon such as expert surgeons operate in a relaxed posture with the armrest and novice surgeons tend to take an excessive wrist extension and elbow extended posture. In this pilot study, we used an optical motion capture system to analyze the differences in the posture pattern during robotic simulator tasks between surgeons at two skill levels.

Materials and methods

Participants and task

The study protocol was approved by the Ethics Committee, Kansai Medical University, Osaka, Japan (Protocol Number 922). This study included 20 participants: 10 were experienced surgeons who had performed >100 cases of robotic surgery and had more than 15 years of surgical experience, and 10 were assigned to the novice group (medical students with no robotic surgery experience) (Table 1).

We selected two exercises based on a needle driving task in a da Vinci Skills Simulator (DVSS, Intuitive Surgical, Inc., Sunnyvale, California, USA): Suture Sponge 1 task (SP) and Tubes task (TU) (Fig. 1). In SP, the needle had to be passed from one predetermined point to another point on the suture sponge. First, the participant passed the needle from the top point to the bottom point with the right hand three times. The exercise was then repeated with the left hand. The needle was then passed from the bottom point to the top point with the right hand, and repeated with the left hand three times. In TU, the needle had to be passed through eight points that appeared in order in a tube similar to the intestinal tract. In TU, needle driving was operated with the right hand. Before performing these tasks, novice group practiced for 1 week (30 min to 1 h a day) under an instructor's guidance, while the experienced surgeons practiced each task several times.

Measurement

The participants' upper body motion during each simulated surgical task was captured with the commercially available optical motion tracking system OptiTrack Flex3 (NaturalPoint, Inc., Corvallis, Oregon, USA), using six infrared cameras and retroreflective markers of 14 mm spherical diameter. A sampling frequency of 100 Hz was used to capture tracking data from each marker. Post-procedural processing of the kinematic data was analyzed in Motive:-Body (NaturalPoint, Inc., Corvallis, Oregon, USA). Fifteen markers were used to track the head, shoulder, elbow (lateral and medial), wrist (lateral and medial), hand, and hip for motion capture (Fig. 1). All marker trajectories that vibrated faster than 6 Hz frequency were smoothed. An optical motion capture system can measure three-dimensional coordinates with an extremely small degree of error. Although a few meters squared of space is required to install the camera, it is suitable for analyzing elaborate movements in a limited space, such as during a surgical procedure.

Outcome measures

We evaluated the automated scoring system of the DVSS, including the operators' performances in eight categories and an overall score (time to complete the exercise, economy of motion, instrument collision, excessive instrument force, instrument force, instrument out of view, master workspace range, drops, and missed targets). According to the surgeons' point of view, we defined the x axis as in front and behind, the y axis as up and down, and the z axis as right and left. The location information was used to calculate the joint angles [axilla (x–y plane: θ_1, y–z plane: θ_3), elbow (x–y plane: θ_2), wrist (flexion–extension: θ_4)], the percentage of time when the wrist height was lower than the elbow height (PTW), and the height of the elbow/wrist relative to the armrest. The axillary angle was defined as the angle formed by the hip, the shoulder, and the lateral of the elbow marker, while the elbow angle was defined as the angle formed by the shoulder, the lateral of the elbow, and the lateral of the wrist marker. The wrist angle was defined as the angle formed by two normal vectors consisting of each of three points (1: hand, medial wrist, lateral wrist, 2: lateral elbow, lateral wrist, medial wrist). All angles were calculated using the cosine theorem:

Table 1 Participant characteristics

Group	Number	Male/ female	Handedness (right/ left)	Career (years)	Robotic surgery (number)	Length of upper arm (cm, average)
Experienced	10	10/0	10/0	16–32	>100	Right 27.4, left 27.1
Novice	10	8/2	10/0	0	0	Right 29.1, left 28.8

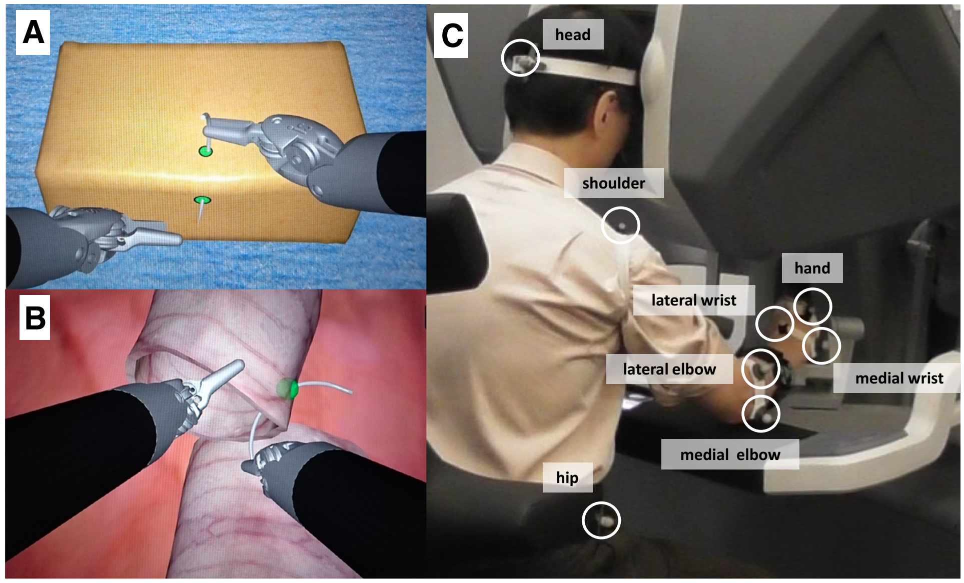


Fig. 1 We selected two exercises based on a needle driving task in a da Vinci Skills Simulator. **A** Suture Sponge 1 task, **B** tubes task. **C** Right side markers. Participants were equipped with fifteen retroreflective markers

$\cos\theta = AB \cdot AC/|AB||AC|$.

For each joint angle, we analyzed the average angle and the average standard deviation of the angle as an indicator of joint stability during each task. If only the average angle was compared, then the variation of the angle during each task could not be evaluated. Measuring the average standard deviation of the angle enabled us to include the time factor in the evaluation.

It is important to assess the ability to adjust the position of the master controller in order to evaluate posture pattern during robotic simulator tasks; hence, we recorded the number of times that each participant used the camera button and the clutch button.

Statistical analysis

Data are expressed as mean ± standard deviation. Statistical analysis was performed by creating SPSS 20.0.0.1 (SPSS, Chicago, IL, USA). All parameters were compared between the two groups using the Mann–Whitney U test. A p value <0.05 was considered statistically significant.

Results

The DVSS scores are shown in Table 2. There were significant differences between groups in all parameters except for "instrument out of view" in both tasks and "missed target" in TU.

The average joint angles and average standard variability angles are shown in Table 3. There were significant differences between groups in the joint angle of θ_2 on the right side in SP and in the joint angles of θ_1 and θ_2 on the right side in TU. Therefore, the elbow joint angle on the right side tended to be more extended in the novice group than in the experienced group. There were also significant differences between groups in the angle variability of θ_1–θ_4 on the right side, θ_4 on the left side in SP, in θ_3 and θ_4 on the right side, θ_1 and θ_4 on the left side in TU.

With respect to wrist angle, we examined every 10° separately (from 0° to 50°) because there were significant differences in the average standard deviation angle between the two groups on both sides in both tasks (Fig. 2). Novice group showed significantly more excess extension (>50°) in both wrist angles than experienced group in SP and in the right wrist angle in TU (Fig. 2). There was no significant difference when comparing wrist angle distribution every 10 degrees.

Figure 3 shows the differences in the PTW, which differed significantly between groups in the SP on the right side (experienced group: 9.22 ± 11.24, novice group: 66.83 ± 25.28, $p < 0.001$) and the left side (experienced group: 23.11 ± 20.71, novice group: 58.70 ± 36.43, $p < 0.001$), and in TU on the right side (experienced group: 10.69 ± 12.66, novice group: 68.64 ± 24.96, $p < 0.001$). There was no significant difference between groups in TU on the left side (experienced group: 19.96 ± 29.37, novice group: 38.35 ± 32.48, $p = 0.082$).

Table 4 shows the height of the elbow and wrist relative to the armrest. In SP, the average height of the elbow in the novice group was significantly higher than in the experienced group on the right side, and the percentage of time when the elbow rose more than 5 cm from the armrest was also significantly higher in novice group versus experienced group on both sides. In TU, the percentage of time when the elbow rose more than 5 cm from the armrest was significantly higher in the novice group compared with the

Table 2 Skill simulator score including the operators' performances in eight categories

Task	Suture Sponge 1			Tubes		
Group	Experienced	Novice	*p* value	Experienced	Novice	*p* value
Overall score	87.9 ± 7.4	62.0 ± 15.1	0.001*	72.4 ± 13.6	56.6 ± 10.9	0.028*
Time to complete expertise	185.9 ± 22.9	283.5 ± 73.8	0.002*	209.0 ± 20.0	264.5 ± 40.6	0.006*
Economy of motion	224.3 ± 26.0	324.9 ± 84.5	0.005*	352.7 ± 35.6	475 ± 83.9	0.004*
Instrument collision	1.9 ± 2.3	9.3 ± 6.9	0.001*	3.3 ± 2.45	7.8 ± 2.9	0.005*
Excessive instrument force	0 ± 0	1.4 ± 2.7	0.030*	0 ± 0	1 ± 2.1	<0.001*
Instrument out of view	0 ± 0	0 ± 0	–	0.4 ± 0.8	1.3 ± 2.1	ns
Master workspace range	3.3 ± 0.46	4 ± 0.7	0.015*	5.3 ± 2	7.8 ± 1.1	0.007*
Drops	0 ± 0	0.4 ± 0.7	0.030*	–	–	–
Missed targets	7.2 ± 3.5	19.9 ± 8.8	0.002*	5.8 ± 6.8	3.2 ± 2.0	ns

Experienced group: surgeons who had performed >100 robotic surgeries and had >15 years of surgical experience ($n = 10$)

Novice group: medical students with no robotic surgery experience ($n = 10$)

Values are presented as the mean (SD)

* $p < 0.05$

experienced group on the right side. The average height of the wrist in the novice group was significantly lower than in the experienced group on the right side in both tasks. There was no significant difference between groups on the left side, although the novice group tended to have a lower wrist height than the experienced group.

The total number of times that each participant used the camera button and the clutch button was significantly less for the novice group in both tasks (SP: experienced group 4.5 ± 5.4 times, novice group 0.8 ± 1.0 times, $p = 0.003$; TU: experienced group 26.6 ± 12.3 times, novice group 8.8 ± 3.8 times, $p < 0.001$).

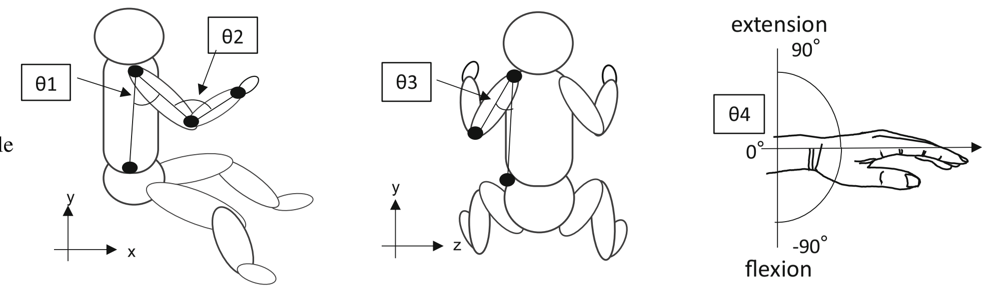
Discussion

This study analyzed differences in the posture patterns during robotic simulator tasks between novice and experienced surgeons using an optical motion capture system (OptiTrack). Our data showed that the PTW was greater in novice group, as those in the novice group tended to elevate the elbow and perform tasks using the lower portion of the upper limb.

With progress in engineering technology, several studies have quantified operative maneuvers to assist in acquiring efficient surgical skills such as the applied force patterns of suture techniques, dissection maneuvers [16–19], and forceps tip motion tracking [20, 21]. Regarding posture analysis, low-cost motion capture systems will continue to be developed and used for motion analysis. In the field of sports, motion analysis has been used for instruction and coaching of golf swing [22]. Kinect (Microsoft, Corp., Redmond, WA, USA) is a popular motion analysis system that was introduced in 2012. Motion analysis has also been used for postural analysis during endoscopic procedures such as upper gastrointestinal endoscopy and colonoscopy [9, 10]. The distance between both hands was different among surgeons of different skill levels, and keeping the hands wider apart kept the colonoscope straight and allowed fine control of the tip of the endoscope. For novice surgeons, early exposure to tips regarding surgical maneuvers would help shorten the learning curve. Advice on proper posture may also prevent chronic injury and lead to earlier proficiency. In this study, we used the OptiTrack system, which consistently produces positional error of less than at least 0.3 mm [23]. As Kinect cannot quantify the overlapping parts of the body and record the motion pattern of torque steering, such as forearm supination and pronation, it would be difficult to use Kinect to evaluate fine movements such as finger movement.

Recently, the field of ergonomics for preventing musculoskeletal injury in robotic surgery has attracted a lot of attention. It is generally considered that robotic surgery systems relatively provide surgeons with a good ergonomic work environment. Hubert et al. reported that physical workload during standard laparoscopies was significantly greater than during robotic surgery using an objective assessment sheet (NASA-TLX), and surgeon heart rate during standard laparoscopy was significantly increased compared with during robotic surgery [1]. Zhini et al. also compared the ergonomic differences between robotic and laparoscopic surgery using surface electromyography, and found that laparoscopic surgery elevated bicep, tricep, and deltoid activation compared with robot-assisted surgery [2]. However, another report showed that even in robot-assisted laparoscopic prostatectomy, neck and back pain was present in 23% of urologists [3]. Lee et al. reported that 236 surgeons (56.1%) practicing robotic surgery complained of physical symptoms or discomfort; neck

Table 3 Joint average angle and average standard deviation angle



	Task	Group	Right side				Left side			
			θ_1	θ_2	θ_3	θ_4	θ_1	θ_2	θ_3	θ_4
Average angle (°)	Suture Sponge 1	Experienced	37.28 ± 6.09	103.84 ± 7.96	24.88 ± 15.99	21.85 ± 2.55	34.39 ± 6.3	107.49 ± 9.47	26.02 ± 15.34	24.88 ± 15.99
		Novice	37.04 ± 10.76	119.28 ± 7.53	23.36 ± 11.00	22.42 ± 3.87	31.99 ± 8.29	108.66 ± 6.05	23.88 ± 4.49	23.36 ± 11.00
		p value	ns	0.001*	ns	ns	ns	ns	ns	ns
	Tubes	Experienced	31.99 ± 5.05	98.23 ± 5.79	18.52 ± 7.53	23.30 ± 5.74	31.96 ± 8.23	96.84 ± 11.44	24.21 ± 5.69	18.52 ± 7.53
		Novice	39.47 ± 8.84	122.69 ± 13.18	16.34 ± 6.43	28.65 ± 7.01	34.83 ± 6.86	107.16 ± 12.67	25.06 ± 3.59	16.34 ± 6.43
		p value	0.041*	<0.001*	ns	ns	ns	ns	ns	ns
Average standard deviation angle (°)	Suture Sponge 1	Experienced	2.85 ± 1.13	5.65 ± 1.19	2.54 ± 0.77	13.76 ± 2.55	4.31 ± 1.75	6.37 ± 1.6	2.89 ± 1.82	15.03 ± 1.90
		Novice	5.3 ± 1.71	8.41 ± 2.87	4.64 ± 1.42	18.60 ± 3.87	4.88 ± 1.71	7.91 ± 2.84	3.66 ± 2.28	17.72 ± 2.83
		p value	<0.001*	0.023*	0.004*	0.019*	ns	ns	ns	0.013*
	Tubes	Experienced	4.5 ± 1.82	7.81 ± 1.72	3.75 ± 2.22	14.75 ± 1.65	7.34 ± 2.13	11.36 ± 2.17	5.23 ± 1.63	22.24 ± 3.24
		Novice	5.98 ± 1.96	8.84 ± 1.81	6.25 ± 2.68	18.95 ± 2.86	9.33 ± 1.83	12.66 ± 1.52	5.92 ± 2.51	31.49 ± 4.34
		p value	ns	ns	0.019*	0.004*	0.049*	ns	ns	0.038*

Experienced group: surgeons who had performed >100 robotic surgeries and had >15 years of surgical experience ($n = 10$)

Novice group: medical students with no robotic surgery experience ($n = 10$)

Values are presented as the mean (SD)

* $p < 0.05$

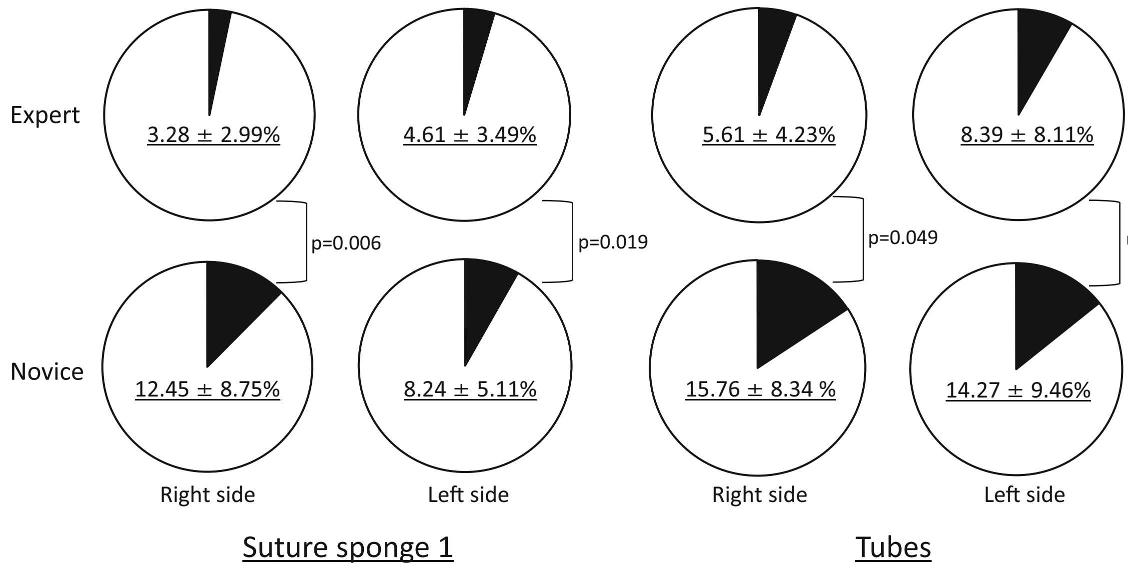


Fig. 2 Percentage time in which the wrist angle was extended beyond 50°. Experienced group: surgeons who had performed >100 robotic surgeries and had >15 years of surgical experience ($n = 10$); novice group: medical students with no robotic surgery experience ($n = 10$). Values are presented as the mean (SD). *Mann–Whitney U test. The *black section* of the pie chart indicates the percentage time in which the wrist angle was extended beyond 50°

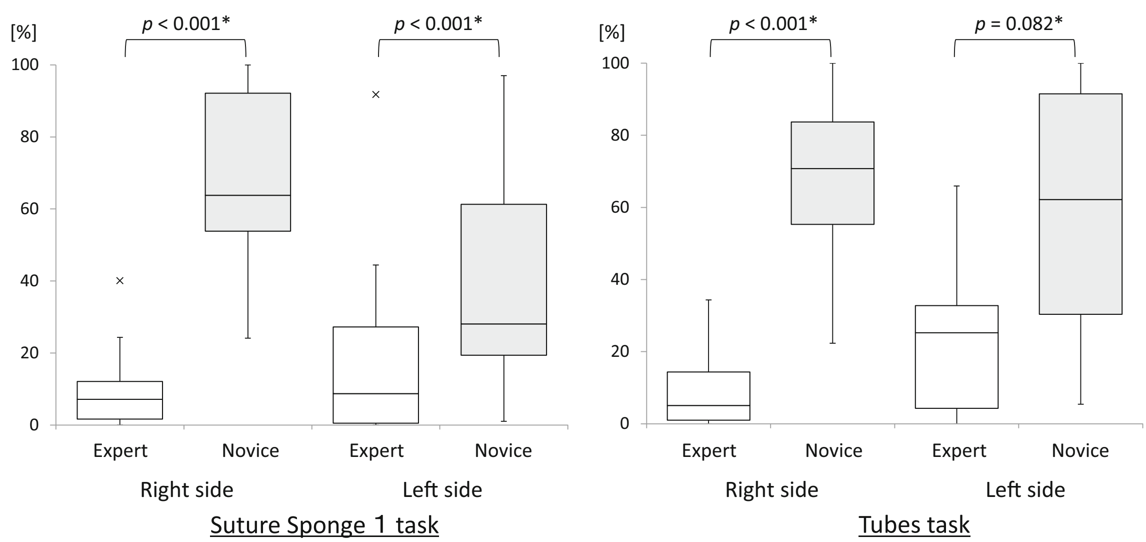


Fig. 3 The percentage of time when the wrist height was lower than the elbow height (PTW). Expert group: surgeons who had performed >100 robotic surgeries and had >15 years surgical experience ($n = 10$), novice group: medical students with no robotic experience ($n = 10$). The PTW significantly differed between groups in the SP on *both sides*, and in the TU on the *right side*. *Mann–Whitney U test

stiffness, and finger and eye fatigue were the most common symptoms [4]. Megan et al. also reported that of 250 surgeons who currently performed >50% of procedures robotically ($n = 122$), laparoscopically ($n = 67$), or via open surgery ($n = 61$), the rate of physical symptoms was significantly higher in the robotic group (72%) than in the laparoscopic (57%) or open surgery group (49%). Even in robotic surgery, unnatural postures can cause musculoskeletal complaints and lower performance during surgical procedures [5].

Generally, surgeons seem to experience less fatigue during robotic surgery when they hold their joints in optimal position. Novice surgeons sometimes twist their hands and extend their elbows while performing operative maneuvers. In contrast, an experienced surgeon may fix their elbow on padded armrests in a more relaxed posture. Advancements in engineering technology have enabled analysis of surgical maneuvers in various approaches. The use of an armrest during robotic surgery decreases operator fatigue because of the reduction of the workload of the

Table 4 The height of the elbow and wrist relative to the armrest

Task	Group	Right side			Left side		
		Elbow		Wrist	Elbow		Wrist
		Height (cm)	More than 5 cm (%)	Height (cm)	Height (cm)	More than 5 cm (%)	Height
Suture Sponge 1	Experienced	0.89 ± 0.37	1.36 ± 1.41	4.10 ± 2.53	0.94 ± 0.37	1.17 ± 2.52	2.20 ± 3.01
	Novice	2.49 ± 1.90	18.90 ± 23.62	0.68 ± 1.80	1.61 ± 1.01	7.38 ± 9.03	0.65 ± 1.85
	p value	0.034*	0.005*	0.005*	ns	0.042*	ns
Tubes	Experienced	1.41 ± 0.76	4.29 ± 8.94	5.49 ± 2.30	1.99 ± 0.63	10.54 ± 8.04	5.64 ± 4.53
	Novice	2.30 ± 1.23	13.52 ± 16.18	−0.85 ± 3.30	2.14 ± 0.95	13.08 ± 10.18	2.84 ± 2.59
	p value	0.042*	0.014*	<0.001*	ns	ns	ns

Experienced group: surgeons who had performed >100 robotic surgeries and had >15 years of surgical experience ($n = 10$)

Novice group: medical students with no robotic surgery experience ($n = 10$)

Values are presented as the mean (SD)

* $p < 0.05$

forearm [14]. Yang et al. [14, 15] reported the development of a pressure surveillance system that alarmed when the operator's forearms were not in contact with the armrest. Group training with the alarm has produced good results using the da Vinci Trainer robotic simulator. Training with the alarm was able to improve the proper use of the armrest and help train the novice surgeons to relax during robotic maneuvers.

Our study compared the upper body motion pattern during simulated surgical tasks conducted by novice group versus experienced group. There were significant differences between groups in the dominant elbow joint angle (θ_2) in SP and TU. The average θ_2 angle of the novice group was larger by about 15°–20° compared with the experienced group. The elbow angle of the novice group extended further than 90 degrees, which is a good limb position for the elbow, but may strain the musculoskeletal system. We also found significant differences in the average standard deviation angle of θ_1–θ_4 on the right side and θ_1, θ_4 on the left side (Table 3). This indicates that although it is not so large range, novice group have an unstable position and many unnecessary movements. Furthermore, there were significant differences between groups for the PTW during SP on both sides and for the PTW during TU on the right side (Fig. 3, Table 4). These results indicate that novice surgeons tended to extend their elbows (holding the elbow higher relative to the armrest) and keep the wrist in a lower position relative to the armrest than did the experienced group. Lifting the elbow from the armrest reduces operational stability and promotes fatigue of the shoulder, and a low working area leads to extension of the elbow and wrist. The current results regarding the elbow position supports the previous findings [14, 15]. We found little difference between groups in the overall parameters of the left side in TU. This may be because the left hand only played an assisting role, while the needle driving was done by the right hand. There are two factors that adjust the position of the master controller to make it easier to operate: the camera button and the clutch button. In both tasks, the participants used the camera button and the clutch button significantly less in the novice group; this indicates that the novice group did not take a posture that would make it easier to perform tasks, and tended to work in a relatively low position and extend their arms.

As for the wrist angle, Yu et al. reported the impact of three types of laparoscopic tool handle configurations on wrist posture [8]. Generally, excessive wrist flexion and extension more than 15° from neutral poses a risk of musculoskeletal strain. The ergonomic risks of musculoskeletal strain could be reduced by using the appropriate handle angle, with the pistol-type tool handle configuration recommended as most appropriate. In our study, novice group tended to experience stronger flexion at angles of more than 50° than the experienced group. This indicates that the novice group has a greater risk of musculoskeletal problems (Fig. 2).

The position of the wrist and elbow joints was very different between the experienced group and the novice group. This ergonomic information has a possibility to minimize musculoskeletal problems in the novice group. During a surgeon's career, musculoskeletal problems could lead to chronic diseases, decrease in quality of life, and even absence from work. Hence, surgeons need to undertake training to increase awareness about ergonomics during endoscopic surgery, and to learn to adopt a relaxed natural posture that minimizes muscle stress. Tjiam et al. [24] reported that about 89% of all respondents were willing to improve ergonomic awareness, preferably by integrating ergonomics in hands-on training.

Several limitations of our study must be noted. We did not evaluate the learning curve, and the stages of development of surgical skills still need to be researched. We also did not evaluate the skills during the actual operative procedures but rather just during simulation tasks. Moreover, we did not include experienced surgeons from a high-volume center who had performed >1000 cases of robotic surgery. The motion capture system is reasonably expensive and requires ample working space for the camera setting. However, optical tracking systems have a high accuracy compared with other approaches. In future work, we plan to evaluate the relevance of surgical posture and fatigue using an assessment sheet (e.g., NASA-TLX, SURG-TLX) or surface EMG to evaluate the learning curve for novice surgeons to provide feedback on posture and the role of the hips and legs in controlling the console movements.

In conclusion, the optical motion capture system detected the differences in the posture patterns of novice versus experienced surgeons during robotic simulator tasks. There were differences between the novice group and the experienced group in the positional relationship between the elbow and wrist and joint angle of the upper limb, indicating that the experienced group may have less posture stress. This information would be helpful for the novice group in robotic training to understand how to move their own posture efficiently, and for the establishment of ergonomic guidelines.

Funding This work was supported by JSPS KAKENHI Grant Number 16K11074 and 16K20167.

Compliance with ethical standards

Disclosures Drs. Kenta Takayasu, Kenji Yoshida, Takao Mishima, Masato Watanabe, Tadashi Matsuda, and Hidefumi Kinoshita have no conflicts of interest or financial ties to disclose.

References

1. Hubert N, Gilles M, Desbrosses K et al (2013) Ergonomic assessment of the surgeon's physical workload during standard and robotic assisted laparoscopic procedures. Int J Med Robot 9:142–147
2. Zihni AM, Ohu I, Cavallo JA et al (2014) Ergonomic analysis of robot-assisted and traditional laparoscopic procedures. Surg Endosc 28:3379–3384
3. Bagrodia A, Raman JD (2009) Ergonomics considerations of radical prostatectomy: physician perspective of open, laparoscopic, and robot-assisted techniques. J Endourol 23:627–633
4. Lee GI, Lee MR, Green I et al (2017) Surgeons' physical discomfort and symptoms during robotic surgery: a comprehensive ergonomic survey study. Surg Endosc 31:1697–1706
5. McDonald ME, Ramirez PT, Munsell MF et al (2014) Physician pain and discomfort during minimally invasive gynecologic cancer surgery. Gynecol Oncol 134:243–247
6. Lee G, Lee T, Dexter D et al (2007) Methodological infrastructure in surgical ergonomics: a review of tasks, models, and measurement systems. Surg Innov 14:153–167
7. van Det MJ, Meijerink WJ, Hoff C et al (2009) Optimal ergonomics for laparoscopic surgery in minimally invasive surgery suites: a review and guidelines. Surg Endosc 23:1279–1285
8. Yu D, Lowndes B, Morrow M et al (2016) Impact of novel shift handle laparoscopic tool on wrist ergonomics and task performance. Surg Endosc 30:3480–3490
9. Arnold SH, Svendsen MB, Konge L et al (2015) Three-dimensional motion tracking correlates with skill level in upper gastrointestinal endoscopy. Endoscopy 47:825–828
10. Svendsen MB, Preisler L, Hillingsoe JG et al (2014) Using motion capture to assess colonoscopy experience level. World J Gastrointest Endosc 6:193–199
11. Aitchison LP, Cui CK, Arnold A et al (2016) The ergonomics of laparoscopic surgery: a quantitative study of the time and motion of laparoscopic surgeons in live surgical environments. Surg Endosc 30:5068–5076
12. Kramp KH, van Det MJ, Totte ER et al (2014) Ergonomic assessment of the French and American position for laparoscopic cholecystectomy in the MIS Suite. Surg Endosc 28:1571–1578
13. Yu D, Dural C, Morrow MM et al (2017) Intraoperative workload in robotic surgery assessed by wearable motion tracking sensors and questionnaires. Surg Endosc 31:877–886
14. Yang K, Perez M, Hossu G et al (2017) "Alarm-corrected" ergonomic armrest use could improve learning curves of novices on robotic simulator. Surg Endosc 31:100–106
15. Yang K, Perez M, Perrenot C et al (2016) A new system for evaluation of armrest use in robotic surgery and validation of a new ergonomic concept—armrest load. Int J Med Robot 12:604–612
16. Cundy TP, Thangaraj E, Rafii-Tari H et al (2015) Force-Sensing Enhanced Simulation Environment (ForSense) for laparoscopic surgery training and assessment. Surgery 157:723–731
17. Horeman T, Rodrigues SP, van den Dobbelsteen JJ et al (2012) Visual force feedback in laparoscopic training. Surg Endosc 26:242–248
18. Horeman T, van Delft F, Blikkendaal MD et al (2014) Learning from visual force feedback in box trainers: tissue manipulation in laparoscopic surgery. Surg Endosc 28:1961–1970
19. Yoshida K, Kinoshita H, Kuroda Y et al (2013) Analysis of laparoscopic dissection skill by instrument tip force measurement. Surg Endosc 27:2193–2200
20. Yamaguchi S, Yoshida D, Kenmotsu H et al (2011) Objective assessment of laparoscopic suturing skills using a motion-tracking system. Surg Endosc 25:771–775
21. Uemura M, Tomikawa M, Kumashiro R et al (2014) Analysis of hand motion differentiates expert and novice surgeons. J Surg Res 188:8–13
22. Stančin S, Tomažič S (2013) Early improper motion detection in golf swings using wearable motion sensors: the first approach. Sensors 13:7505–7521
23. Cortes C, Unzueta L, de Los Reyes-Guzman A et al (2016) Optical enhancement of exoskeleton-based estimation of glenohumeral angles. Appl Bionics Biomech 2016:5058171
24. Tjiam IM, Goossens RH, Schout BM et al (2014) Ergonomics in endourology and laparoscopy: an overview of musculoskeletal problems in urology. J Endourol 28:605–611