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ORIGINAL SCIENTIFIC REPORT

A Pilot Study on Measuring Tissue Motion During Carotid Surgery Using Video-Based Analyses for the Objective Assessment of Surgical Performance

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Abstract

Background The 'gentle' handling of tissue (i.e., 'respect for tissue') is a fundamental aspect of surgical performance and learning. To date, there have been no methodological assessments that quantitatively measure 'gentleness.' Therefore, the aims of this study were (1) to propose a novel metric for gentle surgical maneuvers, (2) to validate the feasibility of this methodology, and (3) to explore safer surgical techniques through this methodology.
Methods Using surgical video-based motion software, the motion of the carotid artery around plaque was analyzed and quantified during a carotid endarterectomy. Kinematic parameters (minimum and maximum acceleration, and maximum and mean velocity) were compared among the surgical tasks and techniques, as well as between novice and expert surgeons.
Results The surgical tasks of dissecting the common carotid artery, passing the proximal vessel loops, and ligating vessels showed the highest absolute values of kinematic parameters. Dissections perpendicular to the line of the internal carotid artery tended to show higher kinematic parameters than those in the parallel direction, with blunt dissections typically higher than sharp dissections. The kinematic parameters of novice surgeons were significantly higher than those of experts, and receiver operating curve analysis showed a strong discriminative power.
Conclusion This study shows that tissue motion parameters could be a novel and feasible surrogate marker for the objective assessment on the 'gentleness' of surgical performance. Future studies should be performed to further elucidate the relationship on the direct correlation between tissue kinematic data and clinical outcomes or surgical adverse events.

Introduction

Technical skills are one of the most important and fundamental aspects in surgery and were recently shown to correlate with clinical outcome [1]. However, acquiring sufficient technical skill still continues to remain a matter of intuition rather than reason. Surgical trainees spend many years learning the nuances of such technical skills largely through case observations and hands-on training in the operating room under the qualitative supervision of their mentors in a traditional master-apprentice education model [2, 3]. In order to move toward a more competency-based paradigm, sensitive and reliable metrics for the objective assessment of surgical performances are required [3–5].

Several criteria-based scores, including checklists, have been developed and are often used for this purpose [6, 7]; however, as most of them use subjective judgment scales, they are still prone to multiple biases [8, 9]. To overcome

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this limitation, several studies have utilized novel engineering technologies for the development of objective and quantifiable methods [10] such as force measurement using force sensing tools [2, 3, 11], eye tracking using a head-mounted eye tracker [12], and motion tracking using electromagnetic sensors attached to the surgeon's body or instruments [13–15]. Although each study provided promising results and attractive viewpoints in the assessment of technical skill, these methodologies require special devices or sensors for taking measurements and are therefore difficult to feasibly implement across multiple clinics. Recently, video-based analysis has garnered attention due to the increasing availability of recording devices in the operating theater [16–19], with some studies starting to utilize surgical videos for motion analysis of the surgeon's hands or instruments [20, 21].

Despite these advances, there is no single methodology that has been developed that provides a comprehensive assessment of surgical skill as it requires a variety of complicated, unique, and special surgical finesse [3, 5, 20, 21]. Given this, we propose the use of 'tissue motion' during surgery as a novel metric for an objective and quantifiable assessment. This concept was based on the hypothesis that less tissue motion could be a quantifiable surrogate marker for the 'gentleness' of tissue handling, i.e., 'respect for tissue' during surgical maneuvers.

During carotid endarterectomies (CEA), perioperative stroke and cranial or cervical nerve injuries are the most common major complications and can result in a neurological deficit [22–25]. Many experts have emphasized the importance of careful and gentle manipulation around carotid plaques as rough and careless manipulation around the carotid artery has a potential to cause direct nerve injury and/or plaque disruption that can lead to an embolic source to the brain [22, 24, 26].

Therefore, in this study, we performed surgical video-based motion analysis of the carotid artery during a CEA. The aim of this study was to validate the feasibility of this novel metric through the surgical process of carotid artery exposure and to explore safer techniques through this methodology.

Methods

Surgeon and case selection

This study was performed with institutional approval from Hokkaido University Hospital, Sapporo, Japan. As a part of an exploratory research project on the objective assessment of surgical performance, this retrospective pilot study was designed to compare various tissue motion parameters between two groups: novice and expert surgeons, using already obtained surgical videos during the performance of a CEA. The novice group included senior neurosurgical residents and clinical fellows who had performed less than five CEAs. The expert group included board certified neurosurgeons who had performed over 50 CEAs and over 300 microsurgical procedures independently.

In total, 39 CEA cases were performed between January 2015 and December 2018 at our institution. To remove possible confounding patient factors that may affect kinematic parameters, female patients, patients with obesity (body mass index > 30), and patients with a history of neck surgery or radiation were excluded. Only patients with symptomatic severe carotid stenosis and intraplaque hematoma signals diagnosed via magnetic resonance imaging (MRI) and carotid sonography were included in this study. Of these, there were nine CEA cases in which the six novice surgeons completed carotid artery exposure during a CEA. As a control, the seven most recent CEA cases performed by the four expert neurosurgeons were selected for this study. Patient and surgeon characteristics are summarized in Tables 1 and 2.

Fifteen out of 16 CEAs were performed without any adverse events, and no abnormal signals were found under multimodal monitoring, including motor evoked potential (MEP), somatosensory potential (SEP), and near-infrared spectroscopy (NIRS), throughout the procedures [27–29]. However, in one case (Case 16), a postoperative embolic ischemic stroke was discovered via a postoperative MRI, with a reduction seen in MEP signals after completion of the carotid artery exposure and before clamping the carotid artery.

Surgical procedure and data collection

The procedure for carotid artery exposure was as follows. First, a linear skin incision along the anterior border of the sternocleidomastoid muscle (SCM) was made, and the SCM was retracted posteriorly. Then, we routinely used a surgical microscope to perform the following procedure and a surgical video was recorded through the microscope-mounted video camera device. Dissection was kept along the anterior border of the internal jugular vein while opening the carotid sheath. The common facial vein and retromandibular veins were ligated and cut. The common carotid artery (CCA), internal carotid artery (ICA), external carotid artery (ECA), arterial branches of the ECA (such as the superior thyroid artery), and the ansa cervicalis and hypoglossal nerve were carefully and gently dissected. The carotid sheath was lifted using a rubber hook to make a shallow surgical field, and the vessel loops were inserted under both the distal ICA and proximal CCA.

The process of carotid artery exposure around vulnerable plaques was thought to be the most important process in

Table 1 Patients' characteristics

Group	Expert	Novice	*p* value
Total number of patients	7	9	
Clinical features			
Age (years)	71.7 ± 9.7	70.0 ± 6.5	ns
Symptomatic	7	9	ns
Side	L: 4, R: 3	L: 3, R: 6	ns
Degree of stenosis (%)	79.9 ± 6.7	80.2 ± 10.7	ns
High carotid bifurcation	3	0	$*p < 0.05$
Highly calcified plaque	1	2	ns
Vulnerable plaque	7	9	ns
Perioperative medication			
Single antiplatelet	6	9	ns
Dual antiplatelets	1	0	ns
Risk factors			
Body mass index (BMI)	25.0 ± 2.4	22.9 ± 2.6	ns
Mild obesity (BMI 25–30)	3	1	ns
Hypertension	6	8	ns
Diabetes	3	4	ns
Hyperlipidemia	6	7	ns
Smoking	4	6	ns
Comorbidities			
Coronary artery disease	3	2	ns
Congestive heart failure	1	1	ns
Chronic obstructive pulmonary disease	1	2	ns
Chronic renal failure (dialysis)	1	0	ns
Contralateral carotid arterial occlusion	1	1	ns
Contralateral laryngeal nerve palsy	0	0	ns
Perioperative complication	0	1 (Stroke)	ns

L left, *R* right, *ns* not significant

avoiding surgical complication [23–25]; therefore, video-based analysis was performed from the initial opening of the carotid sheath to clamping of the carotid arteries. In this surgical process, nine surgical tasks were identified by expert consensus: (1) dissecting the ICA; (2) dissecting the CCA; (3) dissecting the ECA; (4) dissecting branches of the ECA including the superior thyroid artery, lingual artery, facial artery, and occipital artery; (5) dissecting the cranial or cervical nerves, including the hypoglossal nerve, ansa cervicalis, and vagal nerve; (6) inserting the vessel loop distal to the ICA; (7) inserting the vessel loop proximal to the CCA; (8) lifting the carotid sheath and rotating the ICA to make a shallow surgical field; and (9) ligating and cutting the vessels, including the common facial vein, retromandibular vein, and occipital artery.

To investigate the correlation between kinematic parameters and surgical dissection techniques, we classified each surgical trial into either a sharp or blunt dissection using the video observations. We also decided whether the dissection was performed in a parallel direction (parallel dissection) or a perpendicular direction (perpendicular dissection) to the line of the ICA.

Video-based analysis

Surgical video clips were divided into segments for each surgical trial and converted into WMV format (720 × 480 pixels, 29.97 frames per second) using a video converter software, TMPGEnc 4.0 XPress® (Pegasys Inc., Tokyo, Japan). In this study, the starting point of each trial began when the surgeon's fingers or instruments came into the operative field (i.e., the video screen), and the ending point was when they disappeared from the operative field. Then, semiautomatic point tracking was conducted using video motion analysis software, MoveTr/2D® (Library Co., Ltd., Tokyo, Japan). Calibration was conducted with the use of a

Table 2 Surgeons' characteristics and cases

Surgeon no.	PGY	Experience		Cases operated	Procedural time (min)	No. of trials
		CEA	Microsurgery			
Expert						
1	27	>200	>1000	Case 1 & 2	59 & 79	85
2	15	>100	>500	Case 3 & 4	30 & 36	42
3	20	>200	>1000	Case 5	81	36
4	25	>150	>1000	Case 6 & 7	42 & 64	41
Novice						
5	8	4	<50	Case 8	78	36
6	7	2	<15	Case 9 & 10	101 & 117	43
7	7	3	<30	Case 11 & 12	85 & 97	54
8	8	2	<40	Case 13 & 14	94 & 101	42
9	4	1	<5	Case 15	99	26
10	5	0	<5	Case 16	87	19

CEA carotid endarterectomy, *PGY* postgraduate year

scale located in the surgical field. The software semiautomatically tracked the target point using a pattern matching algorithm and calculated the kinematic elements including displacement, velocity, and acceleration (Fig. 1). In this study, the distinctive pattern (e.g., the pattern of the vasa vasorum) on the carotid plaques or bifurcation point was manually set as the region of interest (ROI) for tracking in each trial (Fig. 1a). The moment the surgeon's fingers or instruments interrupted the view of the ROI, or if the magnitude of the microscope was changed, the point tracking was temporarily intermitted. The trials in which assistant surgeons may have affected tissue motion were excluded from analyses.

The minimum and maximum values of acceleration from each trial were used to represent the deceleration and acceleration profiles, respectively (Fig. 1c). The maximum values of velocity were used to represent the velocity profile in each trial (Fig. 1c). Since the duration of each trial varied, the mean values of velocity were used to represent the replacement of the target point in each trial (Fig. 1c).

Statistics

Statistical analyses were conducted using SPSS Statistics® version 24.0 (IBM, Chicago, Illinois, USA) and EXCEL-TOUKEI 2012® (Social Survey Research Information Co., Ltd., Tokyo, Japan). The normality of the data was investigated using Shapiro–Wilk's test. Normally distributed continuous data were compared using Welch's t test between the two groups, and non-normally distributed data were compared using Mann–Whitney U tests. The data from each surgical task were compared with the data from the control task, i.e., dissecting the ICA, using the Kruskal–Wallis test followed by the Steel test. A $p < 0.05$ was considered to be statistically significant.

Receiver operating characteristic (ROC) curves based on the kinematic parameters relevant to the surgeon's level were calculated. The area under the curve (AUC) with a 95% confidence interval (CI) was calculated and used to evaluate the discriminative accuracy of the kinematic parameters to predict the surgeon's skill level.

Results

Kinematic profiles and surgical tasks

In total, 485 trials were identified through the surgical videos. Of these, 61 trials (overall 12.5%) were excluded from analyses as these videos were not available for analysis (e.g., out of focus, out of view, etc.). Therefore, kinematic data were acquired from 424 trials. The mean and standard deviation (SD) of each kinematic parameter (the minimum and maximum acceleration, and maximum and mean velocity) across the nine surgical tasks are summarized in Table 3.

The kinematic parameters varied across the surgical tasks. Of these, the absolute values for each kinematic parameter (minimum acceleration, maximum acceleration, maximum velocity, mean velocity) in dissecting the CCA ($p < 0.05$, $p < 0.05$, $p < 0.01$, and $p < 0.01$, respectively), in passing the proximal vessel loops ($p < 0.05$ in minimum acceleration and $p < 0.01$ in mean velocity), and in ligating

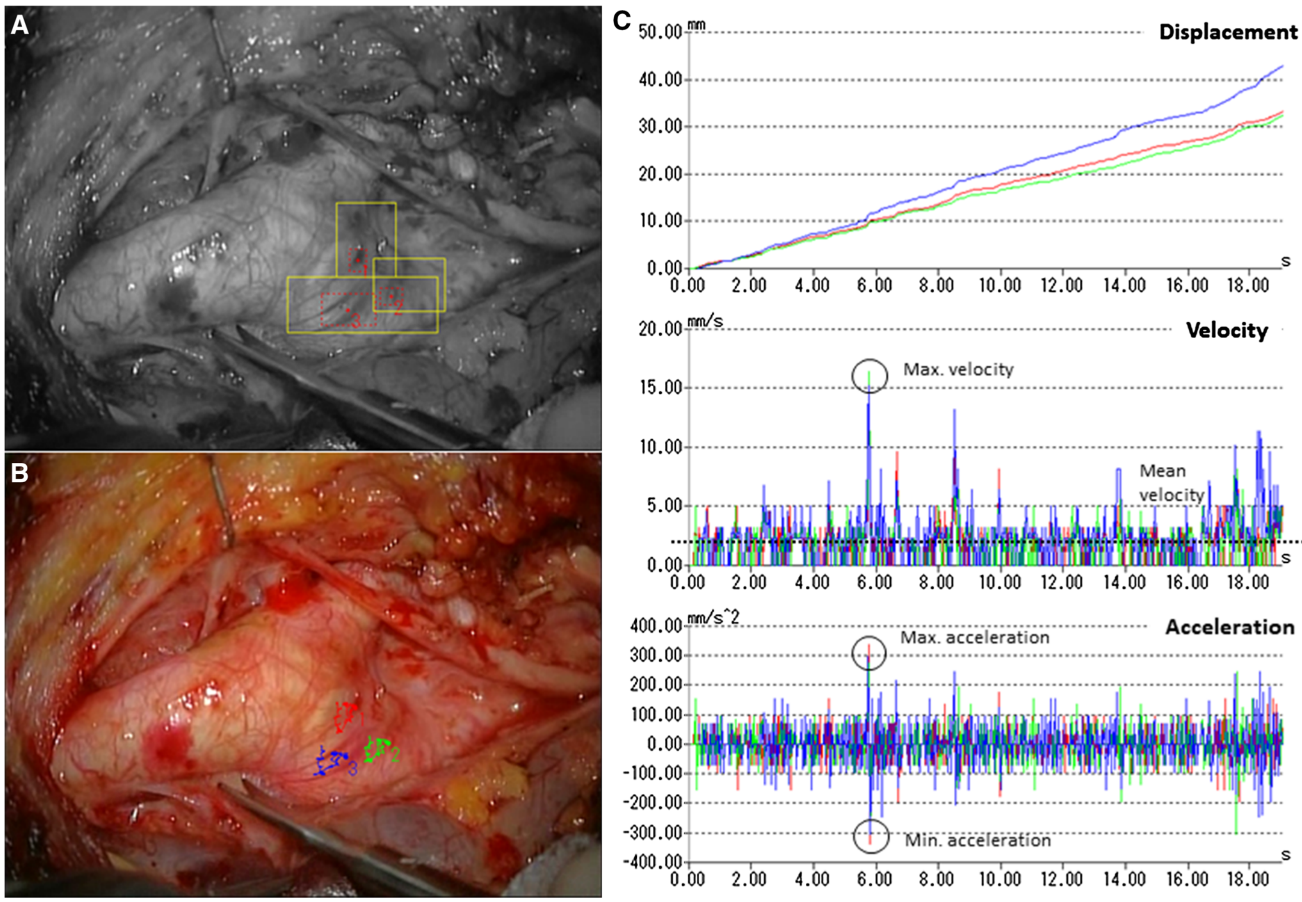


Fig. 1 Example of motion analysis. Target point was set to the distinctive pattern on the carotid plaque or bifurcation (**a**), and tracked semiautomatically by video motion analysis software, MoveTr/2D® (**b**); the software calculates the kinematic elements, including displacement, velocity, and acceleration (**c**). The minimum and maximum values of acceleration (black circle), and the maximum (black circle) and mean (dotted line) values of velocity were used for analysis to represent the kinematic parameters

Table 3 Surgical tasks and acquired kinematic parameters

Surgical tasks	No. of trials	Kinematic parameters (mean ± SD)			
		Min. acceleration (mm/s^2)	Max. acceleration (mm/s^2)	Max. velocity (mm/s)	Mean velocity (mm/s)
Dissecting ICA	115	−296.0 ± 194.6	299.1 ± 208.2	14.32 ± 9.60	2.402 ± 1.183
CCA	66	−375.1 ± 267.3*	358.5 ± 231.7*	18.43 ± 11.09**	2.785 ± 1.053**
ECA	79	−298.3 ± 159.7	279.9 ± 164.1	14.07 ± 7.91	2.343 ± 0.927
Branches	50	−327.7 ± 186.0	289.9 ± 183.5	15.36 ± 8.59	2.406 ± 0.846
Nerves	25	−324.2 ± 274.0	283.0 ± 212.1	14.84 ± 12.75	2.165 ± 0.912
Passing proximal v-loop	29	−481.5 ± 413.4	479.2 ± 386.6*	21.63 ± 15.86	2.768 ± 0.647**
distal v-loop	30	−259.9 ± 138.1	268.2 ± 153.3	11.01 ± 5.90	1.933 ± 0.774
Lifting carotid sheath	19	−284.9 ± 89.6	274.0 ± 80.7	11.85 ± 3.51	2.183 ± 0.646
Ligating vessels	11	−918.4 ± 972.9**	758.0 ± 610.6 **	35.02 ± 35.43	3.441 ± 2.534

CCA common carotid artery, *ECA* external carotid artery, *ICA* internal carotid artery, *SD* standard deviation, *v-loop* vessel loop

*$p < 0.05$; **$p < 0.01$ when compared with the task of dissecting ICA

the vessels ($p < 0.01$ in minimum acceleration and $p < 0.01$ in maximum acceleration) were significantly higher than those in the task of dissecting the ICA.

Comparison between dissection techniques

The results comparing the parallel and perpendicular dissections, and sharp and blunt dissection are shown in Fig. 2.

The absolute values of each kinematic parameter during the perpendicular dissection tended to be significantly higher than those during the parallel dissection ($p < 0.01$ for all parameters), with those in the blunt dissection also significantly higher than those in the sharp dissection ($p < 0.01$ for all parameters).

Comparison between novice and expert

Results comparing the novice and expert groups in all trials are shown in Fig. 3. The absolute value of each kinematic parameter of the novice surgeons was significantly higher than that of the expert surgeons ($p < 0.01$ for all parameters). Figure 3b shows the ROC curves for each kinematic profile, with relatively strong associations for each parameter reflected by the AUC with 0.74 (95% CI 0.69–0.80) for the minimum acceleration, 0.75 (95% CI 0.70–0.81) for the maximum acceleration, 0.76 (95% CI 0.71–0.81) for the maximum velocity, and 0.76 (95% CI 0.71–0.81) for the mean velocity.

The mean and SD of each kinematic parameter for each individual case are shown in Fig. 4. The absolute mean of each kinematic parameter of novices was significantly

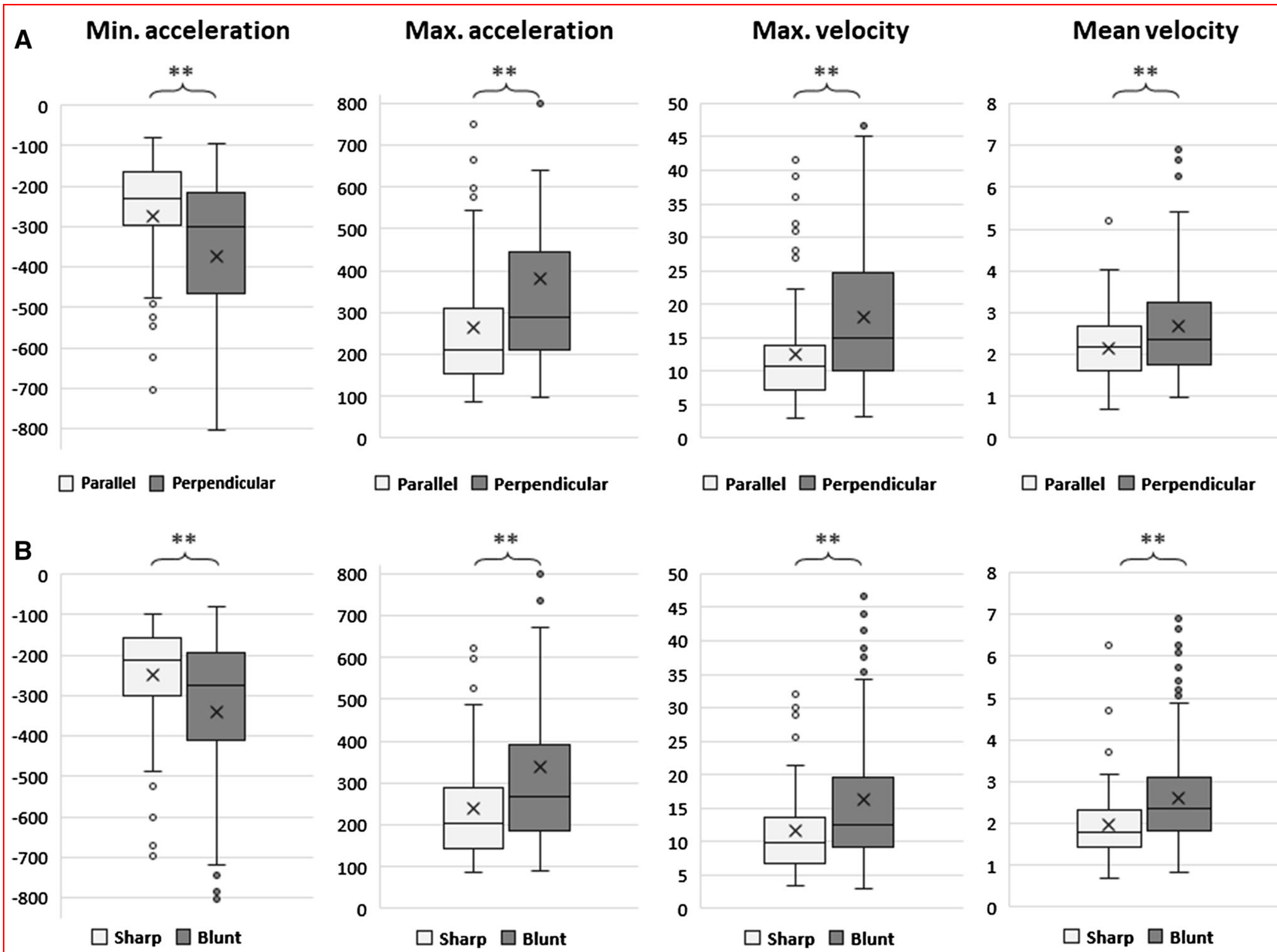


Fig. 2 **a** Comparison between parallel and perpendicular dissections to the course of the internal carotid artery (ICA). Perpendicular dissections tend to be higher for each kinematic parameter. **b** Comparison between sharp and blunt dissections. Blunt dissections clearly show higher kinematic parameters. **$p < 0.01$

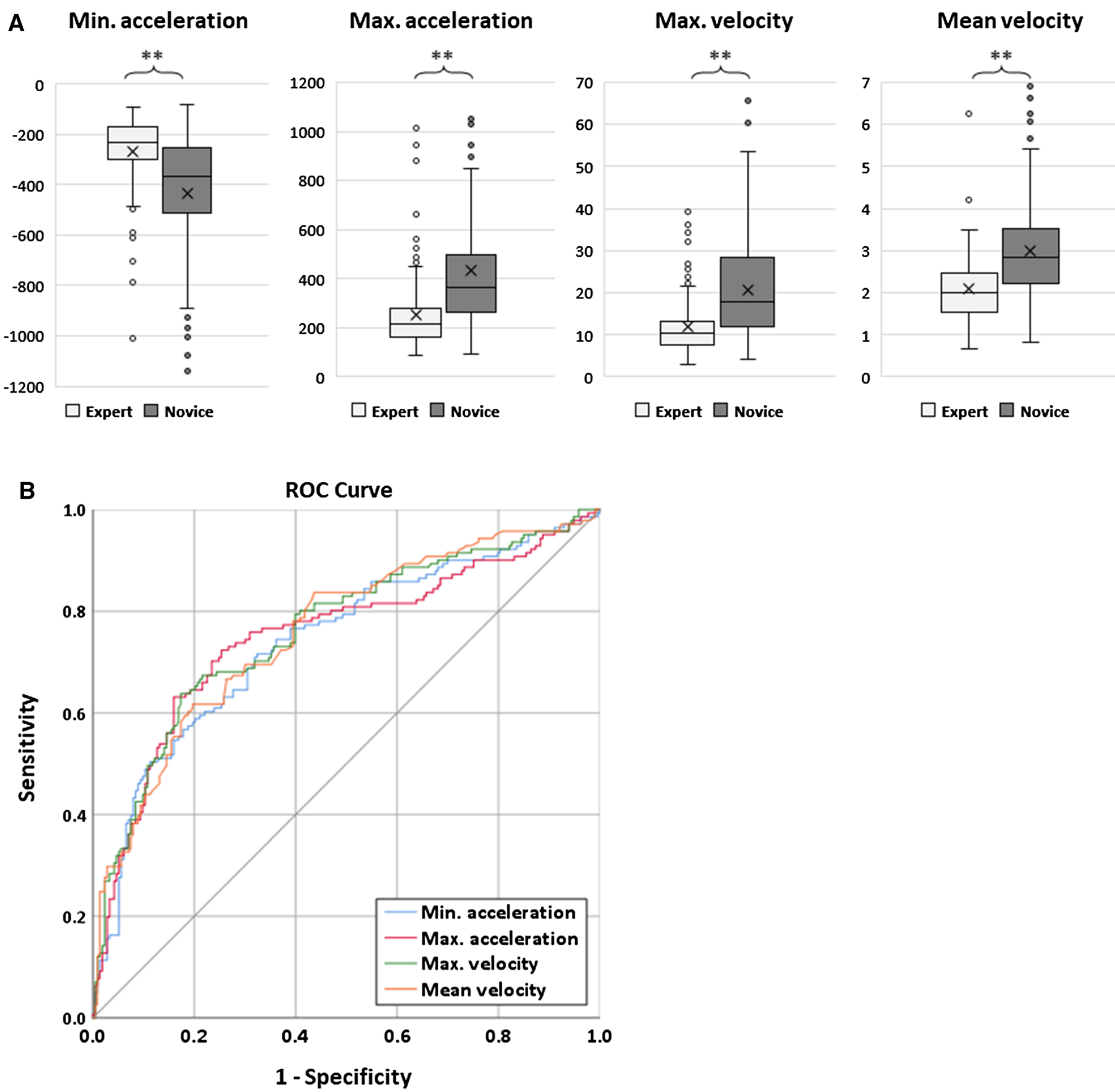
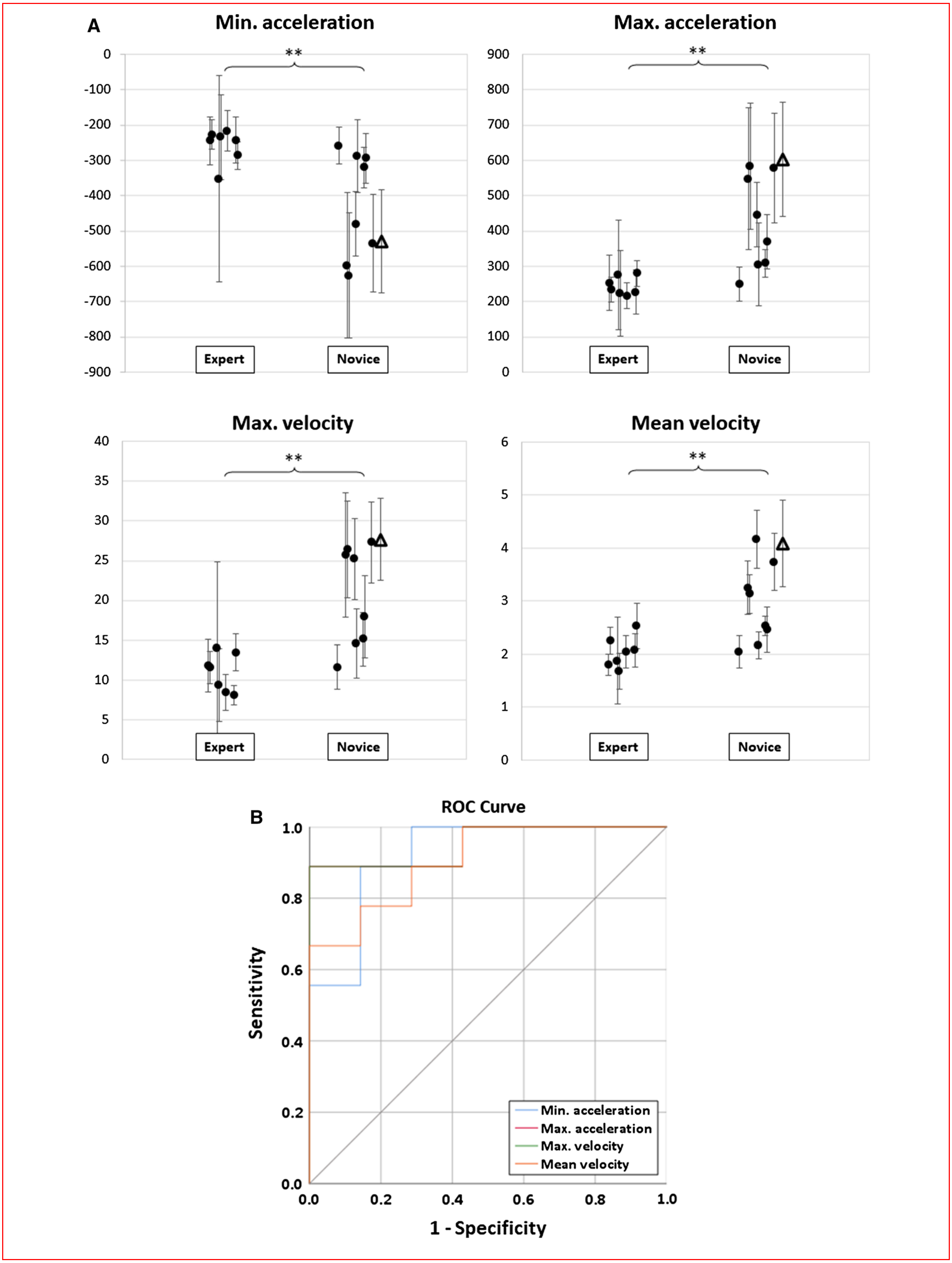


Fig. 3 **a** Comparison between the novice and expert surgeon's kinematic parameters from all trials. The novice surgeon group clearly show higher kinematic parameters in their surgical maneuvers. **b** Receiver operating characteristic (ROC) curves demonstrated the ability of each kinematic parameter in predicting the surgeon's level. Area under the curve (AUC) for the minimum acceleration, the maximum acceleration, the maximum velocity, and the mean velocity is 0.74 (95% confidence interval [CI] 0.69–0.80), 0.75 (95% CI 0.70–0.81), 0.76 (95% CI 0.71–0.81), and 0.76 (95% CI 0.71–0.81), respectively. $^{**}p < 0.01$

higher than that of experts ($p < 0.01$ for all parameters). Interestingly, the parameters of the case in which we encountered ischemic complication (Case 16) had the highest maximum acceleration and maximum velocity. Figure 4b shows the ROC curves of each mean kinematic profile for each individual case, with strong associations for each parameter reflected by the AUC, with 0.92 (95% CI 0.78–1.00) for the minimum acceleration, 0.95 (95% CI 0.85–1.00) for the maximum acceleration, 0.95 (95% CI 0.85–1.00) for the maximum velocity, and 0.91 (95% CI 0.76–1.00) for the mean velocity.


A
Min. acceleration
Max. acceleration
Max. velocity
Mean velocity
Expert
Novice
**
B
ROC Curve
Sensitivity
1 - Specificity
Min. acceleration
Max. acceleration
Max. velocity
Mean velocity

◀**Fig. 4** **a** Mean kinematic parameters in each individual case. The cases operated by the novice surgeon group clearly show a higher mean value. Triangle symbols indicate the case of postoperative ischemic stroke (Case 16). **b** Receiver operating characteristic (ROC) curves demonstrate a strong ability of mean kinematic parameters from each individual case in predicting the surgeon's level. Area under the curve (AUC) for the minimum acceleration, the maximum acceleration, the maximum velocity, and the mean velocity is 0.92 (95% confidence interval [CI] 0.78–1.00), 0.95 (95% CI 0.85–1.00), 0.95 (95% CI 0.85–1.00), and 0.91 (95% CI 0.76–1.00), respectively. $^{**}p < 0.01$

Discussion

To our knowledge, this was the first study that focused on the motion of the tissue, which is the main object in surgical maneuvers. Based on Newton's second law, the acceleration of the tissue is produced by net forces on the tissue. Therefore, less acceleration of the tissue represents lower net forces on the tissue; therefore, this could theoretically be a surrogate marker of gentleness or respect for the tissue during a surgical maneuver. Since less displacement of tissue could represent better motion economy during a surgical maneuver, velocity or displacement could also be a surrogate marker of surgical performance.

As a pilot study, we compared kinetic parameters between novice and expert surgeons and were able to clearly show differences between the two groups. These results support our hypothesis that these metrics could be useful in the objective assessment of surgical skill, which is necessary not only to assure patient safety by ensuring surgeon competence, but also to provide information on training progress, credentialing, and on the standardization of surgeries. Through feedback information, trainees can clearly track their progress and try to get closer to the experts' level of performance by highlighting the areas of weaknesses or errors. In addition, such an objective and quantifiable measurement could also be utilized as a normative catalogue to develop futuristic surgical devices, such as in robotics, computer simulations, and safety devices through the implementation of a high acceleration warning system [2, 30]. The concept of this study is in line with the concept of 'surgical data science' that has recently emerged as a new scientific field in medicine to improve the quality of interventional healthcare [31].

Surgical task and technique

In this study, the kinetic parameters in the surgical tasks of ligating vessels, dissecting the CCA, and passing proximal vessel loops were significantly higher than the parameters for dissecting the ICA. Given these results, we may conclude that special attention should be taken when surgeons perform those tasks. As the size of the CCA is usually larger than the ICA, the forces exerted by the surgeons were higher when manipulating the CCA compared to the ICA. What was surprising was that kinematic parameters when dissecting branches of the ECA or nerves were not different from those during the dissection of the ICA, even though these structures were a little further away from the plaque site where we set the ROI. Therefore, surgeons should also perform gentle maneuvers when manipulating around the branches of the ECA or cranial nerves. Since parallel and sharp dissections tend to be lower than perpendicular and blunt dissections, these techniques should be used more frequently when the situation is appropriate.

Strength of this methodology

As previously mentioned, the strength of this methodology is that the assessment of surgical performance can be easily conducted in clinical situations using this methodology. Although a clinical study could not completely account for possible confounding patient factors that could affect surgical performance, there are still several advantages as follows. During surgical training, while several surgical models or simulators have been used, none represent ideal surgical scenarios or are 100% similar to the situation of an actual surgery, including not only in the physical property, but also in terms of mental pressure. Therefore, the kinematic data presented in this study provide a true representation of kinematic data during a carotid surgery. Moreover, this methodology could be theoretically applied to any type of video clip (e.g., roof-mounted camera in the operating room, endoscopic camera, etc.) and could still be useful in other types of surgical maneuvers. As this methodology uses surgical videos, we could also simultaneously discover near misses, errors, or adverse events through video observation while analyzing the kinematic data [2, 3, 19]. The relationship between those events and the kinematic data would be an interesting next step in research.

Limitations and future work

The main limitation of this study was the lack of direct correlation with clinical or surgical outcomes as this study included a limited number of cases. Although we encountered one case of postoperative ischemic stroke, which was thought to be associated with surgical maneuvers, the kinematic data related to such unexpected events are still insufficient. Considering this limitation, our research group is planning to conduct future research with a larger case cohort that analyzes the correlation between kinematic data and clinical results, including postoperative imaging and multimodal intraoperative monitoring, such as transcranial Doppler sonography, MEP, SEP, and NIRS [23, 24, 27–29].

A fundamental limitation of this methodology is that the kinematic data could only be obtained in limited stages of the CEA (i.e., only from the initial opening of the carotid sheath to the clamping of the carotid arteries) since the ROI could not be set during other stages of the CEA. Other surgical tasks, such as removing carotid plaques or suturing carotid arteries, should also be investigated in the future. However, as the detection of microembolic signals during carotid exposure has been shown to correlate with ischemic complications during CEAs [24, 32], this methodology could represent one of the most significant surgical performances during a CEA.

Another fundamental limitation was the lack of three-dimensional (3D) kinematic data. While motion analyses use sensors that enable us to obtain 3D data [13], in principle, it is difficult to attach motion sensors to the tissue. For a more comprehensive understanding of kinematic data, 3D data that include data on depth are required. However, 2D data acquired in this study cover the most important planes and directions since most microsurgical procedures are conducted in the same plane that is under the microscope's focus.

Conclusion

We conclude that tissue motion parameters could be a novel and feasible surrogate marker for the objective assessment of surgical performance. Such an objective measurement might be applicable toward enhancing surgical education and risk management. Future studies should be conducted to further elucidate information on the direct correlation between tissue motion data and the clinical outcomes and/or surgical adverse events.

Compliance with ethical standards

Conflict of interest The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this manuscript.

Informed consent Informed consent was obtained from all individual participants included in this study.

References

1. Birkmeyer JD, Finks JF, O'Reilly A et al (2013) Surgical skill and complication rates after bariatric surgery. N Engl J Med 369:1434–1442
2. Sugiyama T, Gan LS, Zareinia K et al (2017) Tool-tissue interaction forces in brain arteriovenous malformation surgery. World Neurosurg 102:221–228
3. Sugiyama T, Lama S, Gan LS et al (2018) Forces of tool-tissue interaction to assess surgical skill level. JAMA Surg 153:234–242
4. van Hove PD, Tuijthof GJ, Verdaasdonk EG et al (2010) Objective assessment of technical surgical skills. Br J Surg 97:972–987
5. Szasz P, Louridas M, Harris KA et al (2015) Assessing technical competence in surgical trainees: a systematic review. Ann Surg 261:1046–1055
6. Aoun SG, El Ahmadieh TY, El Tecle NE et al (2015) A pilot study to assess the construct and face validity of the Northwestern Objective Microanastomosis Assessment Tool. J Neurosurg 123:103–109
7. Martin JA, Regehr G, Reznick R et al (1997) Objective structured assessment of technical skill (OSATS) for surgical residents. Br J Surg 84:273–278
8. Darzi A, Smith S, Taffinder N (1999) Assessing operative skill. Needs to become more objective. BMJ 318:887–888
9. Kalu PU, Atkins J, Baker D et al (2005) How do we assess microsurgical skill? Microsurgery 25:25–29
10. Rutherford DN, D'Angelo AL, Law KE et al (2015) Advanced engineering technology for measuring performance. Surg Clin North Am 95:813–826
11. Zareinia K, Maddahi Y, Gan LS et al (2016) A force-sensing bipolar forceps to quantify tool-tissue interaction forces in microsurgery. IEEE/ASME Trans Mechatron 21:2365–2377
12. Richstone L, Schwartz MJ, Seideman C et al (2010) Eye metrics as an objective assessment of surgical skill. Ann Surg 252:177–182
13. Ghasemloonia A, Maddahi Y, Zareinia K et al (2017) Surgical skill assessment using motion quality and smoothness. J Surg Educ 74:295–305
14. Harada K, Morita A, Minakawa Y et al (2015) Assessing microneurosurgical skill with medico-engineering technology. World Neurosurg 84:964–971
15. Grober ED, Roberts M, Shin EJ et al (2010) Intraoperative assessment of technical skills on live patients using economy of hand motion: establishing learning curves of surgical competence. Am J Surg 199:81–85
16. Sarkiss CA, Philemond S, Lee J et al (2016) Neurosurgical Skills assessment: measuring technical proficiency in neurosurgery residents through intraoperative video evaluations. World Neurosurg 89:1–8
17. Sugiyama T (2017) Mastering intracranial microvascular anastomoses—basic techniques and surgical pearls. MEDICUS SHUPPAN Publishers Co., Ltd, Osaka, p 209
18. Sugiyama T, Kazumata K, Asaoka K et al (2015) Reappraisal of microsurgical revascularization for anterior circulation ischemia in patients with progressive stroke. World Neurosurg 84:1579–1588
19. Bonrath EM, Gordon LE, Grantcharov TP (2015) Characterising 'near miss' events in complex laparoscopic surgery through video analysis. BMJ Qual Saf 24:516–521
20. Glarner CE, Hu YY, Chen CH et al (2014) Quantifying technical skills during open operations using video-based motion analysis. Surgery 156:729–734
21. McGoldrick RB, Davis CR, Paro J et al (2015) Motion Analysis for microsurgical training: objective measures of dexterity, economy of movement, and ability. Plast Reconstr Surg 136:231e–240e
22. Maniglia AJ, Han DP (1991) Cranial nerve injuries following carotid endarterectomy: an analysis of 336 procedures. Head Neck 13:121–124
23. Muller M, Reiche W, Langenscheidt P et al (2000) Ischemia after carotid endarterectomy: comparison between transcranial Doppler sonography and diffusion-weighted MR imaging. AJNR Am J Neuroradiol 21:47–54

24. Oikawa K, Kato T, Oura K et al (2017) Preoperative cervical carotid artery contrast-enhanced ultrasound findings are associated with development of microembolic signals on transcranial Doppler during carotid exposure in endarterectomy. Atherosclerosis 260:87–93
25. Udesh R, Natarajan P, Thiagarajan K et al (2017) Transcranial Doppler monitoring in carotid endarterectomy: a systematic review and meta-analysis. J Ultrasound Med 36:621–630
26. Smith JL, Evans DH, Gaunt ME et al (1998) Experience with transcranial Doppler monitoring reduces the incidence of particulate embolization during carotid endarterectomy. Br J Surg 85:56–59
27. Alcantara SD, Wuamett JC, Lantis JC 2nd et al (2014) Outcomes of combined somatosensory evoked potential, motor evoked potential, and electroencephalography monitoring during carotid endarterectomy. Ann Vasc Surg 28:665–672
28. Malcharek MJ, Ulkatan S, Marino V et al (2013) Intraoperative monitoring of carotid endarterectomy by transcranial motor evoked potential: a multicenter study of 600 patients. Clin Neurophysiol 124:1025–1030
29. Uchino H, Nakamura T, Kuroda S et al (2012) Intraoperative dual monitoring during carotid endarterectomy using motor evoked potentials and near-infrared spectroscopy. World Neurosurg 78:651–657
30. Sutherland GR, Lama S, Gan LS et al (2013) Merging machines with microsurgery: clinical experience with neuroArm. J Neurosurg 118:521–529
31. Moccia S, Wirkert SJ, Kenngott H et al (2018) Uncertainty-aware organ classification for surgical data science applications in laparoscopy. IEEE Trans Biomed Eng 65:2649–2659
32. Gaunt ME, Martin PJ, Smith JL et al (1994) Clinical relevance of intraoperative embolization detected by transcranial Doppler ultrasonography during carotid endarterectomy: a prospective study of 100 patients. Br J Surg 81:1435–1439