Quantitative Analysis of a Camera Operation for Endoscopic Sinus Surgery Using a Navigation Information: Clinical Study

Takaaki Sugino (Student member)¹, Ryoichi Nakamura²⁻⁴⁻⁶, Akihito Kuboki⁴, Osamu Honda³, Masashi Yamamoto⁴, Nobuyoshi Ohtori⁴

¹ Graduate School of Engineering, Chiba University
² Center for Frontier Medical Engineering, Chiba University
³ Faculty of Engineering, Chiba University
⁴ Department of Otorhinolaryngology, The Jikei University School of Medicine

Abstract

A high level of surgical skill is required for endoscopic sinus surgery (ESS), a procedure that involves the nasal sinus, which is adjacent to important organs, without injury. However, it is difficult to assess such surgery quantitatively in a clinical environment. Thus, we employed a surgical navigation system that is currently used in ESS, and have developed a method to assess surgical tasks by utilizing the navigation system as a recording medium. Previously, we had developed a method for analyzing the manipulation of an endoscope, which is an important aspect of ESS, using this navigation system, based on simulated surgeries. Here, we established a method for measuring and analyzing endoscope manipulation during clinical image-guided ESS. In this study, we analyzed 8 clinical cases, in which expert surgeons treated one nasal cavity, and resident surgeons treated the contralateral cavity, by ESS. In order to clarify the features of endoscopic manipulation by experts and residents in detail, we performed principal component analysis as well as time-series analysis using the analytical parameters derived from information stored on the navigation system. Our proposed method enabled quantitative evaluation of the performance of endoscopic manipulation during ESS in a clinical environment.

Key words

Surgical task evaluation, Endoscopic manipulation, Endoscopic sinus surgery, Surgical navigation, Clinical study

1. Introduction

Advanced surgeries, such as endoscopic surgery, are widely performed, but it is difficult to achieve safety in these surgical procedures. For example, in the field of otolaryngology, although endoscopic sinus surgery (ESS) is commonly performed as a treatment for chronic sinusitis, ESS requires sophisticated psychomotor skills and a knowledge of the relationship of nasal sinuses to vulnerable adjacent structures (i.e., the orbit, or the base of the skull), which, when injured, would have major consequences, such as loss of vision or cerebrospinal fluid leak. Thus, an image-guided navigation system is increasingly used to enhance the safety of ESS. However, as reported in the literature, complications related to ESS still occur despite the use of the navigation system. In order to enhance the safety of this surgery further, it is essential to improve surgeons' levels of the relevant knowledge and skills. Therefore, methods for quantitatively measuring, analyzing, and evaluating surgical tasks or workflow are increasingly being proposed. These approaches can be categorized according to the means of surgical data acquisition. One is an observer-based approach, which uses manually acquired data to analyze surgical procedures. For instance, Neumuth et al. have proposed a method for modeling the surgical process based on the analysis of surgical data.
on surgical data acquired with software they had developed\(^7\); these data included the actions performed, the anatomical structures treated, and the surgical instruments used. The other is a sensor-based approach, which includes automated recording of surgical data and analysis of these data using cameras\(^8\), radio frequency identification tags\(^9\), or instrument trackers\(^10\) in the operating room. For instance, Oropesa et al.\(^8\) have presented a method for tracking and analyzing the motion of surgical instruments based on endoscopic video analysis to assess psychomotor skills during surgery. However, generally, observer-based approaches require a vast amount of time and energy to record surgical data and may include human error in the data, while sensor-based approaches may require complicated preparation and settings for data acquisition (e.g., arrangement or calibration of measurement systems in the operating room), which negatively affects the surgical environment or surgeon’s performance. Thus, in a clinical environment, it is desirable to achieve acquisition of high-quality information related to a surgery in a way that does not require complicated preoperative or intraoperative settings.

As a way to resolve these challenges, we have developed a method that uses a surgical navigation system as a device for recording surgical data, with a view to surgical skill assessment\(^11\)–\(^15\). The navigation system is a device that shows the positional relationship between a patient’s anatomical structure and the surgical instruments used during surgery, based on the medical image and information about the position and orientation of the surgical instruments. We have applied the data acquired via the navigation system to surgical task analysis, although the data are conventionally used only for image guidance. This allowed us to acquire detailed surgical data and simultaneously simplify the setting for data acquisition, because no additional measuring devices were needed for image-guided surgery. To date, we have developed methods for quantifying and evaluating surgical performance during image-guided glioma surgery\(^13\), laparoscopic cholecystectomy\(^14\), and ESS\(^15\) by using the information recorded by the navigation system. In particular, in the case of ESS, in which a surgeon performs the procedure as solo surgery without a scopist by manipulating an endoscope with the left hand and forceps with the right hand, we focused on the manipulation of the endoscope, although other surgical instruments, such as forceps, have often been tracked for analysis in the literature\(^10\)–\(^12\). In a previous study\(^8\), we developed and validated a navigation information-based method for analysis of endoscope manipulation during the simulation of a simple surgical task in ESS, using a phantom of a skull bone. Here, we aimed to establish a method for using the navigation system to measure and analyze the performance of endoscope manipulation during actual image-guided ESS in the operating room. To our knowledge, this is the first attempt to measure and analyze surgeons’ endoscope manipulation during ESS in a clinical setting.

2. Materials and methods
2.1 Clinical study setup
2.1.1 Dataset

In this study, 8 image-guided ESSs, which were performed in the Department of Otorhinolaryngology of the Jikei University School of Medicine, were analyzed. The details of each surgery are presented in Table 1. Three expert surgeons and 5 resident surgeons, who had performed more than 300 ESSs with over 5 years of experience in endoscopic surgery and less than 30 ESSs in the first to third years of their residency each, respectively, participated in this study. Two out of 3 expert surgeons, surgeons A and B, were board certified by the Otorhinolaryngological Society of Japan. For analysis, cases who required ESS for treatment of both the left and right nasal cavities were selected by an expert surgeon, in order to reduce the influence of differences in disease severity on the analysis. For each surgery, either the left or the right nasal cavity was treated by an expert surgeon, while the treatment of the contralateral cavity was performed by a resident surgeon; thus, the endoscope manipulation was measured for a total of 16 procedures. Fig. 1 shows the anatomical structure of the nasal sinus. In this study, we focused on the manipulation of the straight-viewing endoscope during surgical procedures involving the ethmoid sinus. The ethmoid sinus can be divided by a third basal lamella into 2 sections, i.e., the anterior and posterior ethmoid sinuses. We selected surgical procedures involving only the anterior ethmoid sinus as a target for analysis, as procedures involving the posterior ethmoid sinus
require more sophisticated surgical skills, and need to be performed only by expert surgeons to ensure safety. We also divided the target procedure into multiple stages to analyze the endoscope manipulation during each task in detail. The segmentalized stages are as follows:

Stage 1: Removal of the nasal polyp (when applicable)
Stage 2: Removal of the uncinate process
Stage 3: Removal of the ethmoid bulla
Stage 4: Removal of the third basal lamella

As shown in Table 1, since we included patients who did not have nasal polyps (i.e., patient 4), the data for cases do not include the information about endoscope manipulation during stage 1. An oblique-viewing endoscope, which is more difficult to manipulate than the straight-viewing endoscope, were not used for the procedures during all the stages in this study.

2.1.2 Data acquisition

The clinical setup for data acquisition is shown in Fig. 2. It is difficult to retrieve the information on instrument motion from the current commercially available navigation systems, because they are not designed to use the information for a purpose other than guidance of surgery. Thus, in this study, we used an optical tracking system (Polaris Spectra, Northern Digital Inc., Waterloo, Canada), which is equivalent to those used in the commercially available navigation systems. As shown in Fig. 2, the tracking system was fixed to that of the navigation system (ENT Navigation Application, Brainlab, Munich, Germany) so that the measuring ranges of the 2 tracking systems were matched. Additionally, in order to measure the location of the endoscope relative to the patient’s anatomy, calibration for tracking the tip of the endoscope and

<table>
<thead>
<tr>
<th>Patient</th>
<th>Expert ID</th>
<th>Nasal cavity</th>
<th>Total operating time</th>
<th>Resident ID</th>
<th>Nasal cavity</th>
<th>Total operating time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>Right</td>
<td>9 min 37 s</td>
<td>D</td>
<td>Left</td>
<td>26 min 05 s</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>Left</td>
<td>13 min 06 s</td>
<td>D</td>
<td>Right</td>
<td>32 min 04 s</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>Right</td>
<td>10 min 45 s</td>
<td>E</td>
<td>Left</td>
<td>23 min 37 s</td>
</tr>
<tr>
<td>4*</td>
<td>A</td>
<td>Right</td>
<td>8 min 43 s</td>
<td>F</td>
<td>Left</td>
<td>24 min 42 s</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>Right</td>
<td>8 min 52 s</td>
<td>G</td>
<td>Left</td>
<td>21 min 56 s</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>Left</td>
<td>9 min 15 s</td>
<td>H</td>
<td>Right</td>
<td>20 min 10 s</td>
</tr>
<tr>
<td>7</td>
<td>B</td>
<td>Left</td>
<td>13 min 59 s</td>
<td>D</td>
<td>Right</td>
<td>29 min 22 s</td>
</tr>
<tr>
<td>8</td>
<td>B</td>
<td>Left</td>
<td>18 min 14 s</td>
<td>H</td>
<td>Right</td>
<td>25 min 30 s</td>
</tr>
</tbody>
</table>

Average 11 min 34 s

Average 25 min 26 s

Note: *Nasal cavity treated by the surgeon, **No task 1 as the patient had no nasal polyps

Fig.1 Sagittal view through ethmoidal sinuses

Fig.2 Clinical setup

Fig.3 Preoperative preparation for measurement: calibration (Left) and registration (Right)
registration of physical space to computed tomography (CT) image space were preoperatively performed as shown in Fig.3. For the calibration, we transformed the measuring point from the origin of a marker, namely the initial measuring point, to the tip of the endoscope, using our original calibration tool as described in our previous study. For the registration, we first set characteristic points on a patient’s face (e.g., the medial canthus) as landmarks, and the physical–to–image registration was performed by matching the landmark points on the physical coordinate system to those on the CT image coordinate system, using a point–based registration method. The points on the physical space were measured with the optical tracking system and the registration tool (4–Marker Passive Probe, Northern Digital Inc., Waterloo, Canada), whereas those on the image space were acquired with software for medical image processing and visualization (3D Slicer, Brigham and Women’s Hospital, Boston, MA, USA).

As a result, as with the commercially available navigation system, log data of the position of the endoscope relative to the patient’s anatomy, which included information about the position of the tip of the endoscope \( L_i = (x_i, y_i, z_i) \) \((i = 1, 2, \ldots, n)\) and the orientation of the rod of the endoscope \( O_i = (\alpha x_i, \alpha y_i, \alpha z_i) \) \((i = 1, 2, \ldots, n)\), were acquired and only the log data during tasks, namely log data distributed in the nasal cavity, were automatically recorded and used for analysis based on the information on relative position. The log data were also precisely segmentalized into the defined stages by recording the start and end of each stage, based on cues from surgeons during surgery. Moreover, a reference marker placed on the forehead of the patient was used to measure motion of the patient’s head during surgery and correct the positional deviation of log data caused by the motion.

The recording and use of surgical data and patient data on clinical cases in this paper were approved by the ethics committee from the Jikei University School of Medicine (No. 27–131 (8016)).

2.2 Quantitative analysis of endoscope manipulation
2.2.1 Parameterization and principal component analysis

On the basis of our previous study, 5 analytical parameters, including distribution density, velocity and acceleration of the tip of the endoscope, rotation of the rod of the endoscope, and volume of the approximate ellipsoid of the log data distribution, were adopted for multidirectional quantification of features of endoscope manipulation during ESS. The definition and equation of the analytical parameters are indicated in Table 2. Although parameters, such as total operating time or total path length of the surgical instrument, are often used for surgical skill assessment in similar studies, these parameters were excluded to find features of endoscope manipulation that do not depend on the operating time, as it can be assumed that with more surgical experience, time–dependent parameters would become lower. All the analytical parameters used in this study were calculated from only the endoscope tracking information. In terms of the distribution density, the parameters were calculated based on a spatial distribution analysis method. The parameters are closer to 0 when the log data are densely distributed, whereas they approximate 1 when the log data are randomly distributed. For the parameter of ellipsoidal volume, the approximate ellipsoid was calculated by transforming a three-dimensional (3D) unit sphere \( X \) to follow a 3D normal distribution \( N(\mu, C) \) with the expected value \( \mu \) and covariance matrix \( C \) of log data distribution, based on the following equation:

\[
Y = AX + \mu
\]

where \( A \) is a lower triangular matrix obtained by Cholesky decomposition \( C = AA^T \) of the covariance matrix \( C \).

Next, we performed principal component analysis (PCA) of the parameters in order to identify potential key factors in endoscope manipulation. First, to eliminate the difference in units between the parameters, each parameter was standardized so that it has a mean of 0 and standard deviation of 1. Second, PCA was applied to the normalized parameters and principal components were calculated. We focused on the principal components with eigenvalues greater than 1 and investigated the analytical parameters.
we defined the sequence $s_N$, speech recognition. Although the DTW algorithm was originally developed for processes of motion data such as velocity vectors time-series analysis. We also applied DTW barycenter averaging (DBA), which is used for alignment and averaging of more than 2 sequences, to the dataset of sequences. The steps of DBA are as follows:

**Step 1** Setting of an initial reference sequence $s_n = \langle ac_i, \cdots, ac_n, \cdots, ac_N \rangle$ for averaging.

**Step 2** Sequence alignment and calculation of the minimum cost path by comparing each sequence in the dataset with the reference sequence, based on DTW.

**Step 3** Calculation of the barycenter $b_n$ of activities corresponding to each other in the sequences.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution density ($D$)</td>
<td>Three-dimensional spatial density of log data distribution</td>
<td>$D = \frac{W}{E(W)} = \frac{1}{n} \sum_{i=1}^{n} d_i$</td>
</tr>
<tr>
<td>Average velocity ($V \ [\text{mm/s}]$)</td>
<td>Rate of change of the position of the endoscope tip</td>
<td>$V = \frac{1}{n} \sum_{i=1}^{n} \frac{dLi}{dt}$</td>
</tr>
<tr>
<td>Average acceleration ($A \ [\text{mm/s}^2]$)</td>
<td>Rate of change of the velocity of the endoscope tip</td>
<td>$A = \frac{1}{n} \sum_{i=1}^{n} \frac{dv_i}{dt}$</td>
</tr>
<tr>
<td>Rotation ($R \ [\text{deg/s}]$)</td>
<td>Rate of change of the orientation of the endoscope rod</td>
<td>$R = \frac{1}{n} \sum_{i=1}^{n} \frac{dr_i}{dt}$</td>
</tr>
<tr>
<td>Ellipsoidal volume ($E \ [\text{mm}^3]$)</td>
<td>Volume of the approximate ellipsoid of log data distribution</td>
<td>$*E = \frac{4}{3} \pi abc$</td>
</tr>
</tbody>
</table>

Note: * $d_i$: the distance in the log data distribution from the jth point to its nearest neighbor point, $E(W)$: the average distance that would be expected if the log data were randomly distributed in the space. * $a$, $b$, $c$: the half-length of each axis of the approximate ellipsoid.

![Fig 4](image-url) Overview of sequence alignment

$$D_{ij} = d(\langle ac_i^{(1)}, ac_j^{(2)} \rangle) + \min \left\{ \begin{array}{c} D_{i-1, j-1} \\ D_{i, j-1} \\ D_{i-1, j} \end{array} \right\}$$ (4) where $d(\langle ac_i^{(1)}, ac_j^{(2)} \rangle)$ is the distance between activities of $s^{(1)}$ and $s^{(2)}$, calculated using activities with normalized parameters. Although the minimum cost path for aligning the sequences can be found by DTW, the algorithm cannot be used basically for simultaneous comparison of 3 or more sequences. We also applied DTW barycenter averaging (DBA), which is used for alignment and averaging of more than 2 sequences, to the dataset of sequences. The steps of DBA are as follows:

**Step 1** Setting of an initial reference sequence $s_n = \langle ac_i, \cdots, ac_n, \cdots, ac_N \rangle$ for averaging.

**Step 2** Sequence alignment and calculation of the minimum cost path by comparing each sequence in the dataset with the reference sequence, based on DTW.

**Step 3** Calculation of the barycenter $b_n$ of activities corresponding to each other in the sequences.

![Table 2](image-url) Analytical parameters

- **Table 2** Analytical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution density ($D$)</td>
<td>Three-dimensional spatial density of log data distribution</td>
<td>$D = \frac{W}{E(W)} = \frac{1}{n} \sum_{i=1}^{n} d_i$</td>
</tr>
<tr>
<td>Average velocity ($V \ [\text{mm/s}]$)</td>
<td>Rate of change of the position of the endoscope tip</td>
<td>$V = \frac{1}{n} \sum_{i=1}^{n} \frac{dLi}{dt}$</td>
</tr>
<tr>
<td>Average acceleration ($A \ [\text{mm/s}^2]$)</td>
<td>Rate of change of the velocity of the endoscope tip</td>
<td>$A = \frac{1}{n} \sum_{i=1}^{n} \frac{dv_i}{dt}$</td>
</tr>
<tr>
<td>Rotation ($R \ [\text{deg/s}]$)</td>
<td>Rate of change of the orientation of the endoscope rod</td>
<td>$R = \frac{1}{n} \sum_{i=1}^{n} \frac{dr_i}{dt}$</td>
</tr>
<tr>
<td>Ellipsoidal volume ($E \ [\text{mm}^3]$)</td>
<td>Volume of the approximate ellipsoid of log data distribution</td>
<td>$*E = \frac{4}{3} \pi abc$</td>
</tr>
</tbody>
</table>

Note: * $d_i$: the distance in the log data distribution from the jth point to its nearest neighbor point, $E(W)$: the average distance that would be expected if the log data were randomly distributed in the space. * $a$, $b$, $c$: the half-length of each axis of the approximate ellipsoid.
aligned with the reference sequence based on the following equation:

\[ b_k = \left( \frac{ac_1^{(1)} + ac_2^{(2)} + \cdots + ac_{\alpha}^{(\alpha)}}{\alpha} \right) \]

where \( \alpha \) is the number of sequences included in the dataset.

Step 4 Iteration of steps 2 and 3 using the barycenter sequence \( s_b = \langle b_1, \cdots, b_n, \cdots, b_l \rangle \) as the reference sequence \( s_r \) until convergence of a total of the minimum cost paths is achieved.

As the sequences can be obtained by aligning the activities corresponding with those of the reference sequence, the sequences have the same length as the reference sequence. The shorter the length of the initial reference sequence is compared to that of sequences in the dataset, the more information included in the sequences may be lost. Thus, we set the sequence with the longest length in the dataset as the initial reference sequence. The sequences finally averaged in the expert and resident groups were then compared to find differences in the processes of endoscope manipulation between these 2 groups.

All program codes for the analyses noted above were implemented with the Statistics Toolbox of MATLAB (MathWorks Inc., Natick, MA, USA).

3. Results

The calculated analytical parameters in expert and resident groups are shown in Fig.5. The calculation results during each stage and the total procedure of stages 1 to 4 were compared between expert and resident groups. The Mann-Whitney U-test was used to find the significance of differences in the calculation results between the 2 groups. The analytical parameters with significant differences \((p < 0.05)\) are indicated by an asterisk in Fig.5. Significant differences were found in some stages for the parameters of distribution density, acceleration, and rotation. Although not all the parameters differed significantly between the 2 groups, the parameters of the expert group, except for rotation, tended to be smaller than those of the resident group.

Fig.6 and Table 3 shows the results of the PCA and the contribution rates of principal components in each stage, respectively. Since the first 2 principal components in all stages, except for stage 4, had eigenvalues exceeding 1, as indicated in Table 3, they were used for evaluation. As an example of the results of the PCA, the results in stage 2 are displayed in Fig.6. Focusing on the loading plot of each parameter in the plane of the first 2 principal component axes (Fig.6 (a)), we found that all the parameters had loadings of around 0.5 in the first axis, whereas only the parameter of rotation had a high loading in the second axis. Thus, the first and second principal components represent a comprehensive parameter including factors of all the parameters and a parameter highly affected by rotation, respectively. The scatterplot of the principal component
scores for the surgical procedures (Fig. 6(b)) indicate that the data in the expert and resident groups tended to be distributed on the positive and negative sides of the second axis, respectively, although there was no characteristic trend in the first axis. These features of the PCA were found not only in stage 2, but in all stages.

In Fig. 7, an example of the sequence alignment is shown to validate the alignment using DTW based on the information of endoscope manipulation, in other words, to check whether the task contents in the sequences aligned matched each other. Although we actually aligned the sequences composed of the feature vector of endoscope manipulation, Fig. 7 presents the sequences described by the task contents. For comparison, Fig. 7(a), (b), and (c) shows the original sequences, the sequences scaled using the uniform scaling, and the sequences aligned with DTW during stage 2 on patient 8, respectively. Compared with the uniform scaling, DTW successfully aligned the sequences so that the contents in the different sequences could correspond to each other. In Fig. 8, the time-series data in the expert and resident groups, which were smoothed for comparison of trend lines by using a moving-average method, are shown in orange and blue, respectively. The difference values obtained by subtracting the sequence of the resident group from that of the expert group are shown in red. In terms of the parameters of velocity and acceleration, the sequences varied more in stages 3 and 4 than in other stages, and the difference values revealed that the sequence of the resident group had higher amplitude and variability than that of the expert group. Conversely, in terms of the parameter of rotation, the experts had sequences with amplitude and variability equivalent to or more than those of the residents.

### Table 3

<table>
<thead>
<tr>
<th>Stage</th>
<th>Principal components</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eigenvalue</td>
<td>2.71</td>
<td>1.33</td>
<td>0.65</td>
</tr>
<tr>
<td>Stage 1</td>
<td>Inertia [%]</td>
<td>54.26</td>
<td>26.63</td>
<td>12.90</td>
</tr>
<tr>
<td></td>
<td>Inertia [%]</td>
<td>61.62</td>
<td>20.55</td>
<td>13.70</td>
</tr>
<tr>
<td>Stage 2</td>
<td>Eigenvalue</td>
<td>3.08</td>
<td>1.03</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>Inertia [%]</td>
<td>66.55</td>
<td>22.74</td>
<td>5.73</td>
</tr>
<tr>
<td>Stage 3</td>
<td>Eigenvalue</td>
<td>4.09</td>
<td>0.55</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Inertia [%]</td>
<td>81.75</td>
<td>10.98</td>
<td>5.01</td>
</tr>
</tbody>
</table>

### Fig. 6

Results of principal components analysis: (a) principal component loadings of the analytical parameters and (b) principal component scores of the surgical procedures on the plane of the first 2 principal components in stage 2.

![Fig. 6](image)

### Fig. 7

An example of the sequence alignment. (a) Original sequences. (b) Sequences scaled using uniform scaling. (c) Sequences aligned using DTW.

![Fig. 7](image)
throughout the procedure. Additionally, the shaded range in Fig. 8 represents a large time warping range, with more activities in the sequence of the resident group assigned to a single activity in the sequence of the expert group; this therefore reflects the range in which the features of endoscope manipulation in the resident group poorly matched those in the expert group. The shaded ranges were clustered in the first half of the sequence during each stage.

4. Discussion

In this study, we first calculated the 5 analytical parameters defined in this study based on information recorded on the navigation system and compared these between the expert and resident groups. As in our previous study (15), the calculation result showed that expert surgeons tended to manipulate the endoscope more efficiently, capturing the affected area from various viewpoints. Since it may be important to reduce the motion of the tip of an endoscope while obtaining wide views in the narrow nasal cavity in order to achieve safe surgery, these calculation results likely reflect important features of endoscope manipulation. In addition, we consider that analyzing the endoscope manipulation during each stage allows more detailed evaluation of the surgical task, considering that the parameters that differed significantly between the 2 groups also varied across stages.

Second, we performed PCA using these analytical parameters to identify parameters suitable for evaluation of endoscope manipulation during ESS. The results shown in Fig. 6 suggested that rotation strongly reflected the difference between the 2 groups. In ESS, in which the endoscope needs to be manipulated in the limited and narrow space of the nasal sinus, rotation is important for obtaining a field of view with the camera, and may be a more critical factor than the other parameters; thus, rotation may be a potentially important factor for assessment of endoscope manipulation skill.

Finally, we performed a time-series analysis to identify features of endoscope manipulation during each stage, based on DBA. As shown in Fig. 8, we found that the sequences of time-series parameters differed across stages. The anatomical structures treated during stages 3 and 4,
namely the ethmoid bulla and the third basal lamella, are located posterior to those treated during stages 1 and 2. The more posterior the operation field is located in the nasal cavity, the more likely it is that the number of insertions and extractions of the endoscope increases, due to the need to remove blood or tissues adhered to the lens, and the endoscope interferes with the surgical instruments manipulated by the right hand during a task. This may explain why the velocity and acceleration were more variable in stages 3 and 4. Furthermore, the shaded ranges, which imply that the endoscope were inefficiently manipulated, were present in the first part during each stage, this is probably because residents required more time to come to understand the patient’s anatomical structure and condition, and decide how the surgical procedure should be performed than did the experts. The delay of surgical decision-making may have resulted in more endoscope manipulations by the residents than by the experts, particularly in the beginning of each stage. The tendency for endoscope manipulation during ESS was further observed in the time-series analysis. However, for more proper assessment, it is important to enhance the accuracy of the sequence alignment and compare the performances during the same or similar task between different surgeries. Although we found the application of DTW to the time-series data about endoscope manipulation enabled the matching of task contents in different sequences as shown in Fig.7, we can expect the improvement of accuracy in the sequence alignment by considering the motion of surgical instruments manipulated by the right hand because the manipulation of the surgical instruments is more strongly correlated with the task contents than that of the endoscope.

The results in this clinical study showed that our analysis method was applicable to quantitative assessment of the performance of endoscope manipulation in clinical cases of ESS. However, surgeons can use an oblique-viewing endoscope instead of the straight-viewing endoscope during ESS, although we focused on the tasks in which only the straight-viewing endoscope is used in this study. In addition, the surgical performance of ESS depends on the skill with which the surgeon can manipulate not only an endoscope, but also other surgical instruments, such as forceps or a microdebrider. It can also be affected by other factors, such as the severity of sinusitis and the individual patient’s anatomical structure. Thus, in future, we also intend to measure and analyze the motion of the oblique-viewing endoscope or surgical instruments manipulated by the right hand, using this navigation system, and include further data from different cases to clarify the effects of the patient’s condition on surgical performance.

5. Conclusion
In this study, we proposed a method for quantitatively measuring, analyzing, and evaluating endoscope manipulation during ESS, using the surgical navigation system as a device for acquiring surgical data. The proposed method was validated in a clinical study that clarified differences in endoscope manipulation between expert and resident surgeons. Based on the proposed method, we were able to measure and analyze surgical data in a clinical setting and identified differences in endoscope manipulation between experts and residents that can be used to assess endoscope manipulation during ESS. In future, we will evaluate the surgical procedure during ESS by combining analysis of endoscope manipulation with that of other surgical instruments and investigate the correlation between surgical performance and the patient’s condition.

Acknowledgment
This study was supported in part by the Grants-in-Aid (KAKENHI) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT : Nos. 23680056, 22650115 and 24103704), the Research Grant (C) from the Tateishi Science and Technology Foundation, and grants from the Nanohana Competition 2015 of Chiba University.

References
4) Neumuth T, Loeb F, Jannin P. Similarity metrics for surgical
19) Sakoe H, Chiba S. Dynamic programming algorithm optimiza-