An Automated Methodology for Assessing Anatomy-Specific Instrument Motion during Endoscopic Endonasal Skull Base Surgery

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Abstract

Objectives Describe instrument motion during live endoscopic skull base surgery (ESBS) and evaluate kinematics within anatomic regions.

Design Case series.

Setting Tertiary academic center.

Participants A single skull base surgeon performed six anterior skull base approaches to the pituitary.

Main Outcomes and Measures Time-stamped instrument coordinates were recorded using an optical tracking system. Kinematics (i.e., mean cumulative instrument travel, velocity, acceleration, and angular velocity) was calculated by anatomic region including nasal vestibule, anterior and posterior ethmoid, sphenoid, and lateral optocrotid recess (IOCR) regions.

Results We observed mean (standard deviation, SD) velocities of 6.14 cm/s (1.55) in the nasal vestibule versus 1.65 cm/s (0.34) near the IOCR. Mean (SD) acceleration was 7,480 cm/s² (5790) in the vestibule versus 928 cm/s² (662) near the IOCR. Mean (SD) angular velocity was 17.2 degrees/s (8.31) in the vestibule and 5.37 degrees/s (1.09) near the IOCR. We observed a decreasing trend in the geometric mean velocity, acceleration, and angular velocity when approaching the pituitary ($p < 0.001$).

Conclusion Using a novel method for analyzing instrument motion during live ESBS, we observed a decreasing trend in kinematics with proximity to the pituitary. Additional characterization of surgical instrument motion is paramount for optimizing patient safety and training.

Keywords

- ▶ surgical instrument motion
- ▶ surgical kinematics
- ▶ endoscopic skull base surgery
- ▶ surgical safety
- ▶ surgical training

Introduction

Complications are rare during endoscopic endonasal skull base approaches to the sella, but when they occur they can be highly

morbid or even fatal. A recent systematic review of reported internal carotid artery (ICA) injuries during endoscopic sinus and skull base surgery revealed a predilection for injury during entry into the sphenoid sinus and while working in and around the

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sphenoid sinus.¹ Our objective was to evaluate instrument kinematics (i.e., motion properties) in the vicinity of critical neurovascular structures during live endoscopic sinus and skull base surgery. Objective instrument motion analysis is essential for providing real-time, quantitative feedback to trainees, establishing expert benchmarks to increase patient safety, evaluating and designing surgical instruments, and peer review of surgical performance.

Previous work found that higher technical skill is associated with improved postoperative outcomes.² Currently, analysis of surgical technique is subjective, performed by *post hoc* video review. Several investigators have sought objective metrics (e.g., instrument travel, velocity, and predictive models) to quantify surgical performance in bench-top models.^{3–14} However, we lack an automated method for quantifying real-time, anatomy-dependent, surgical instrument motion during live surgery.

In our center's experience, we have observed variation in surgical instrument motion during endoscopic endonasal skull base surgery both by skill level and in the context of anatomy. We noted that instrument kinematics vary as a function of surrounding structures such as the proximity to the opticocarotid recess resulting in slower, more conservative movements. Measuring region-specific instrument kinematics provides real-time feedback alerting the surgeon to aberrations in surgeon-specific instrument kinematics within an anatomic region.

The objectives of the current study were twofold. First, we sought to describe surgical instrument kinematics during endoscopic endonasal skull base surgery with respect to anatomic regions and proximity to critical neurovascular structures. Second, we sought to test the hypothesis that surgical instrument velocity, acceleration, and angular velocity decrease with proximity to the skull base and critical neurovascular structures.

Methods

Data collection was approved by the University of Washington Institutional Review Board (# 52114). Surgical instrument motion was passively recorded during six endoscopic endonasal approaches to the pituitary performed by an experienced skull base surgeon (K.S.M.). Patients underwent mask registration using a Stryker® iNtellect Cranial Navigation System (Kalamazoo, Michigan, United States). A Stryker® Universal Tracker was attached to a microdebrider, and the microdebrider was calibrated to the navigation system. Endoscopic maxillary antrostomy, anterior and posterior ethmoidectomy, and sphenoidotomy were performed using an optically tracked microdebrider. The collection of kinematic data did not interfere with the planned surgical procedure.

Data Capture and Processing

Time-stamped Euclidian coordinates were recorded at 10 samples per second and stored as a text file within the navigation computer. The coordinate log was uploaded to a laboratory laptop and processed using MATLAB®R2015A, The MathWorks, Natick, Massachusetts, United States). Anatomic regions were defined using each patient's navigation head CT. A 3D slicer was used to define anatomic region

boundaries (see –**Supplementary Fig. 1**).¹⁵ Regions included the nasal vestibule, anterior ethmoid, posterior ethmoid, sphenoid, and lateral opticocarotid recess (IOCR). The nasal vestibule coordinates were defined by extending a 2 cm radius from points within the center of each nasal vestibule. The anterior ethmoid region was defined by determining the CT coordinates of two coronal planes at the level of the head of the middle turbinate and the junction of the vertical and horizontal segments of the basal lamella. The posterior ethmoid region was defined by determining the CT coordinates of two coronal planes at the junction of the vertical and horizontal segments of the basal lamella and 1 cm anterior to the sphenoid face. The sphenoid region was defined by the intranasal region extending posterior to the coronal CT plane defined 1 cm anterior to the sphenoid face. The IOCR region was defined by extending a 1.5 cm radius from points near the center of both lateral opticocarotid recesses on an axial CT. Euclidian coordinates were used to calculate mean cumulative instrument travel, mean velocity, and mean acceleration for each region. Angular velocity, the change in instrument angle over time, was calculated including mean pitch velocity (i.e., up and down) and mean yaw velocity (i.e., side-to-side). The time (Δt) between each data sample was defined by calculating the inverse of the sampling rate: $\Delta t = \frac{1}{10 \text{ samples per second}}$. Within a given region, we excluded from analysis instantaneous velocities associated with a Δt of more than 200 milliseconds given that the sampling rate could decrease to six samples per second with multiple tool registration and assuming that Δt was more than 200 milliseconds would imply nonconsecutive data samples (e.g., instrument passes in and out of a region).

Statistical Analysis

Summary statistics of surgical instrument kinematics was generated for each region. To test the hypothesis of a trend in velocity, acceleration, and angular velocity by region, we performed linear regression using region as a categorical variable. Velocity and acceleration were log-transformed to normalize residuals for regression model fitting. Regression slopes are represented by β_1 , and inferential hypothesis testing is performed using partial F-tests at an α -level of 0.05 with corresponding 95% confidence interval (CI) presented. Statistical analyses were performed using Stata 14 (StataCorp. 2015. *Stata Statistical Software: Release 14*. College Station, TX: StataCorp LP) statistical programming software.

Results

Mean cumulative instrument travel in the anterior ethmoid, posterior ethmoid, and sphenoid regions are presented for six endoscopic endonasal anterior skull base cases in the –**Table 1** Linear velocity, linear acceleration, and angular velocity are also shown. We note that mean instrument travel was greatest in the posterior ethmoid (4,300 mm; SD: 1,240) and sphenoid regions (4,570 mm; SD: 3,180). Mean (SD) linear velocity and acceleration decreased posteriorly with nadirs at 1.65 cm/s (0.336) and 561 cm/s² (254), respectively. Mean yaw and pitch velocities decreased with proximity to

Table 1 Instrument motion parameters within anatomic regions and in proximity to critical neurovascular structures

	Nasal Vestibule	Anterior Ethmoid	Posterior Ethmoid	Sphenoid	Lateral Opticocarotid Recess
Mean (SD) cumulative instrument travel (mm) ^a	0	1970 (997)	4,300 (1,240)	4,570 (3,180)	0
Mean velocity (cm/s)	6.14 (1.55)	2.03 (0.230)	1.81 (0.230)	1.78 (0.312)	1.65 (0.336)
Mean acceleration (cm/s)	7,480 (5,794)	1300 (465)	1,070 (280)	561 (254)	929 (662)
Mean yaw velocity (degrees/s)	17.2 (8.31)	10.6 (5.37)	8.49 (3.42)	6.34 (1.65)	6.38 (1.77)
Mean pitch velocity (degrees/s)	10.0 (4.11)	8.47 (1.60)	6.72 (0.779)	5.88 (1.20)	5.37 (1.09)

^aMean cumulative instrument travel was not measured in the nasal vestibule and lateral opticocarotid recess regions.

the IOCR illustrating nadirs at 6.34 degrees/s (1.65) and 5.37 degrees/s (1.09), respectively.

►**Fig. 1** illustrates the trend in log-transformed linear velocity and acceleration according to region. The mean log velocity and log acceleration are significantly lower when approaching the sella ($p < 0.001$). We estimate that the geometric mean velocity is 0.76 times lower for each adjacent more posterior region (95% CI: 0.69, 0.84). The geometric mean acceleration is ~0.59 times lower for each adjacent more posterior region (95% CI: 0.47, 0.74).

►**Fig. 2** shows the trend in angular velocity including pitch and yaw velocities as a function of the anatomical region. The mean pitch and yaw velocities are significantly lower in more posterior regions of the skull base approach ($p < 0.005$). The mean pitch velocity decreased by ~1.18 degrees/s for each subsequent posterior region (95% CI: -1.94, -0.412). The mean yaw velocity decreased by 2.59 degrees/s for each subsequent posterior region (95% CI: -4.23, -0.95).

Discussion

Endoscopic endonasal sinus and skull base surgery have substantially decreased morbidity relative to open approaches in indicated cases.^{1,16} However, working in a confined space with a high density of surrounding critical neurovascular structures while lacking stereovision creates a complexity that is mastered with experience. While rates of significant injury are as low as 0.2 to 1.4%, injuries such as inadvertent damage to the ICA and trauma to the optic nerve are devastating and can be lethal as in the case of ICA injury.¹ In the present study, we developed an algorithm for automated assessment of anatomy-specific surgical instrument motion and described instrument kinematics during endoscopic endonasal skull base surgery within anatomical regions of the nasal cavity. We observed a decreasing trend in linear velocity, linear acceleration, pitch and yaw velocity with posterior surgical progression.

Fig. 1 Linear velocity and linear acceleration by anatomic region. *Left panel*, log-transformed mean velocity for each case ($n = 6$) according to anatomic region. *Right panel*, log-transformed mean acceleration magnitude for each case ($n = 6$) according to anatomic region. *Vestibule*, nasal vestibule; *Ant. Eth.*, anterior ethmoid region; *Post. Eth.*, posterior ethmoid region; *Sphenoid*, sphenoid region; *IOCR*, lateral opticocarotid region.

Fig. 2 Angular velocity by anatomic region. Left panel, anatomically segmented, mean pitch velocity for each case ($n = 6$). Right panel, anatomically segmented, mean yaw velocity for each case ($n = 6$). Vestibule, nasal vestibule; Ant. Eth., anterior ethmoid region; Post. Eth., posterior ethmoid region; Sphenoid, sphenoid region; IOCR, lateral opticocarotid region.

To our knowledge, this is the first study to describe surgical instrument motion during actual endoscopic endonasal skull base surgery with respect to clinically relevant anatomic regions and critical neurovascular structures. These findings provide insight into how surgeons operate in reference to instrument location within the nasal cavity. Prior work has focused on surgical kinematics in bench-top models whereas we investigated instrument kinematics during live surgery. Bench-top work using a peg transfer protocol on the *da Vinci*™ robot observed mean velocities up to 10 cm/s and mean angular velocities ranging up to 16.5 degrees/s for experts.⁸ This is similar to our findings in the nasal vestibule where we observed a mean linear velocity of 6.14 cm/s and a mean angular velocity up to 17.2 degrees/s. This novel finding illustrates change in instrument kinematics with respect to anatomical surroundings during live surgery.

Other bench-top models using laparoscopic trainers evaluated construct validity of linear and angular velocity in differentiating surgical skill level further supporting a role for aggregate kinematic measurements in performance assessment.¹⁷ Investigators have also turned to alternative measures of surgical performance using markers of entropy for differentiating novice and expert surgeons.¹⁸ Hand motion and needle driver tip paths have also been assessed in bench-top simulation models.^{3,5,19} The present study builds on these prior studies in two main ways including: (1) establishing a method for automatic instrument motion analysis during live endoscopic endonasal skull base surgery, and (2) providing patient-specific, anatomically segmented instrument motion analysis.

The main clinical implication of the current work is the use of using anatomy-specific surgical instrument kinematics for real-time monitoring of endoscopic endonasal sinus and skull base surgical procedures. Real-time monitoring would provide instantaneous feedback to trainees and operating surgeons

allowing for the detection of instrument kinematics falling outside of the distribution of typical movements in a given anatomical region. Aberrant motions might occur, for example, in the setting of distorted anatomy with loss of landmarks leading to performance of inadvertent instrument motions normally occurring in regions with less proximity to critical neurovascular structures. A recent systematic review observed a propensity for ICA injury while working near the sphenoid.¹ This could be a function of altered or distorted anatomy, instrument slipping, inadvertent debridement of critical structures, or surgeon-specific factors (e.g., failure to recognize anatomy, fatigue). The goal of understanding surgical instrument kinematics is to increase patient safety by characterizing expert benchmarks of normal surgical instrument kinematics with respect to critical anatomy. Additionally, by providing real-time feedback to trainees regarding their movements in reference to the proximity of the skull base and neurovascular structures, individuals could learn to optimize their efficiency and safety in low- and high-risk regions.

Limitations of the current study include using a single surgeon's experience and monitoring a single instrument. This limits the generalizability of these data. Kinematics of other instruments may vary based on physical properties and their intended use. However, the primary objective of the current study was to describe surgical instrument kinematics during endoscopic skull base surgery with respect to critical neurovascular anatomy. Future analysis of additional instruments will be germane to developing and analyzing surgical instruments. The small sample size also affects potential conclusions regarding the precise means of the measured anatomically related kinematic parameters. However, the current study set out to detect a trend in the means based on anatomy. Future studies will validate surgeon-specific instrument kinematics within specific anatomic regions of the skull base providing benchmarks for trainees to increase patient safety.

Conclusions

This study investigated surgical instrument kinematics during endoscopic endonasal skull base surgery with respect to critical neurovascular skull base anatomy. We observed that linear velocity, acceleration, and angular velocity decreased as the surgical instrument approached the skull base. These data illustrate trends in surgical instrument kinematics in the context of surgical anatomy and may be used in the future to increase surgical safety through the development of training modules with real-time feedback and progress evaluations. Furthermore, programming navigation systems with expert benchmark kinematic parameters may assist with mitigating injuries to significant structures via alarms or instrument disabling devices that recognize movements that deviate from benchmark parameters. Additional work is needed to further elucidate surgical kinematics with respect to anatomical regions and increase our understanding of kinematics associated with inadvertent injury during endoscopic endonasal sinus and skull base surgery.

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