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Feasibility of Using Inertial Measurement Units (IMUs) to Augment Cadaveric Temporal Training

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Objective: Insertional speed of cochlear implant electrode arrays (EA) during surgery is correlated with force. Low insertional speed, and therefore force, may allow for preservation of intracochlear structures leading to improved outcomes. Given the importance of low insertional speeds, we investigate the feasibility of using inertial sensors for kinematic analysis during EA insertion to augment otolaryngology-head and neck surgery training.

Methods: Practicing otolaryngology surgeons were recruited and inertial measurement units (IMU; Metamotions+, MBIENTLAB Inc, San Jose, CA) consisting of accelerometers were used to measure hand speed during EA (Cochlear™Nucleus®CI522 cochlear implant with Slim Straight electrode, Cochlear Limited, Sydney, Australia) insertion into a cadaveric cochlea. A mixed regression model was utilized to determine differences in speed across trials within a surgeon.

Results: A total of nine trials were performed by three surgeons. The highest mean ± SD speed obtained was 8.4 ± 1.7 mm/s, and the highest speed was 22.5 mm/s. Mean speed was not significantly different across trials within surgeons ($p > 0.05$).

Discussion: IMUs are relatively inexpensive and relatively easy to use sensors that provide information on variables that may be of interest for otolaryngology resident training. The use of IMUs as part of advanced temporal training for cochlear electrode insertion can provide insight into hand speed, thereby allowing residents to train with specific regard to this variable. Future randomized-controlled trials can be carried out to determine whether IMUs are conducive to lower insertional speeds.

Key Words: cochlear implant, inertial measurement unit, resident training.

Level of Evidence: NA

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INTRODUCTION

Otolaryngology-head and neck surgery (OHNS) residents are required to develop a broad repertoire of surgical procedures. Although all procedures require manual dexterity, some are particularly challenging. Cochlear implant (CI) surgery stands as a relatively challenging procedure for OHNS residents, where the surgeon must minimize intracochlear forces during electrode array insertion to ensure positive hearing outcomes.[1]

Several factors influence the force exerted by the CI electrode array on surrounding intracochlear structures, and studies show that these forces are significantly influenced by the speed with which the electrode array is inserted into the cochlea.[2,3] Excessive speed increases the risk of the electrode array inadvertently crossing from the scala tympani to the scala vestibuli, potentially disrupting the basilar membrane.[4,5] Naturally, deliberate surgical training to acquire the ability to insert the array with consistently low speeds is critical. Although temporal cadaveric dissection remains the essential tool for acquiring proficiency in CI surgical exposure, there is currently a lack of realistic educational models that quantify CI electrode insertion with specific regard to the need for low insertional speeds.

In this study, we leverage a technology that has potential for scalable OHNS-specific training in the cadaveric temporal labs. In recent years, there has been an increasing use of miniature inertial measurement units (IMUs) in clinical settings. These wearables provide data on limb kinematics from on-board accelerometers, magnetometers, and gyroscope. Portability coupled with low cost makes IMUs ideal devices for research in human biomechanics as evidenced by their widespread employment in laboratory-based and clinical work investigating quasi-static and dynamic behaviors such as postural sway and locomotion.[6–9] Our objective is to assess the feasibility of employing IMUs to acquire objective kinematic data quantifying performance during cochlear implant

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electrode insertion in a cadaveric temporal bone laboratory. We will quantify the magnitude and variability of speed during insertion. Feedback on these measures can potentially aid residents in developing this surgical skill and enhance resident training overall.

METHODS

Setting and Participants

The setting was the cadaveric temporal dissection lab at the Indiana University School of Medicine. This study was approved by the local Indiana Clinical and Translational Science Institute Scientific Review Committee (SRC) and Indiana University School of Medicine's institutional review board (IRB#19784). Surgeons were recruited via email. The inclusion criteria were: (1) practicing otolaryngology-head and neck surgeons who specialize in otology/neurotology and (2) surgeons who perform cochlear implants. Although we aim to improve training methods for residents, we recruited practicing surgeons here to demonstrate the feasibility of our approach. We recruited a convenience sample of three practicing otolaryngology surgeons. Data related to the experience of the surgeons participating in the study were collected. Each surgeon signed a consent form after discussing risks and benefits of participating in the study.

Data Collection

Insertion speeds during the insertion procedure were measured using an IMU (Metamotions+, MBIENTLAB Inc, San Jose, CA). IMU sensors are equipped with a gyroscope, barometer, accelerometer, and a magnetometer; however, we used only accelerometer data. The IMU measured $27 \times 27 \times 4$ mm and weighed 0.2 ounces. One IMU was placed along the dorsal aspect of hand along the metacarpals. The goal was to position the IMU as close as possible to the CI electrode. We considered placing the IMU on the forceps, as the speeds of the hand and forceps could differ due to the movement of the fingers relative to the hand. Although the IMU sensor was small enough not to interfere with hand movements, it was not quite small enough to be placed on the forceps without potentially affecting the procedure. Similarly, placing the IMU on the index finger was found to restrict finger movement, hindering the free insertion of the CI electrode. Therefore, we chose to place the IMU on the dorsal hand, as it offered the closest proximity to the CI electrode without hindering the hand motion. Naturally, there were drawbacks associated with this choice, namely that the IMU measured hand motions, including tremor, rather than the electrode motion.

The IMU was attached to the nitrile gloves using nonadhesive sterile tape (3M™ Coban™, Cottage Grove, MN) before starting the insertion of the electrode (Fig. 1). The raw data output by the IMU was captured via BluetoothLE to an iPad 10th generation (Apple Inc., Cupertino, USA) with the MetaBase application (version 4.4.1, MBIENTLAB Inc., San Jose, CA). The sampling rate was 100 Hz.

Experimental Setup

The setup in the cadaveric temporal lab is illustrated in Figure 2. The surgeons were provided a cadaveric temporal bone each to mirror training conditions. Soft-tissue work and bone drilling were performed by the surgeons without the IMU to expose the round window. After adequately exposing the round window and securing the IMU to the hand (as described in Methods), the surgeons were directed to insert the CI electrode array (Cochlear™Nucleus®CI522 cochlear implant with Slim

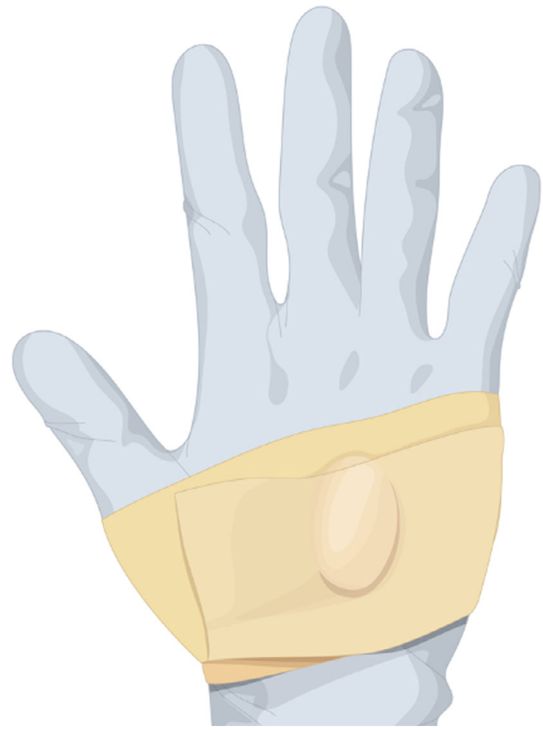

Fig. 1. Illustration of gloved hand with Inertial Measurement Unit (IMU) stabilized in place using tape. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

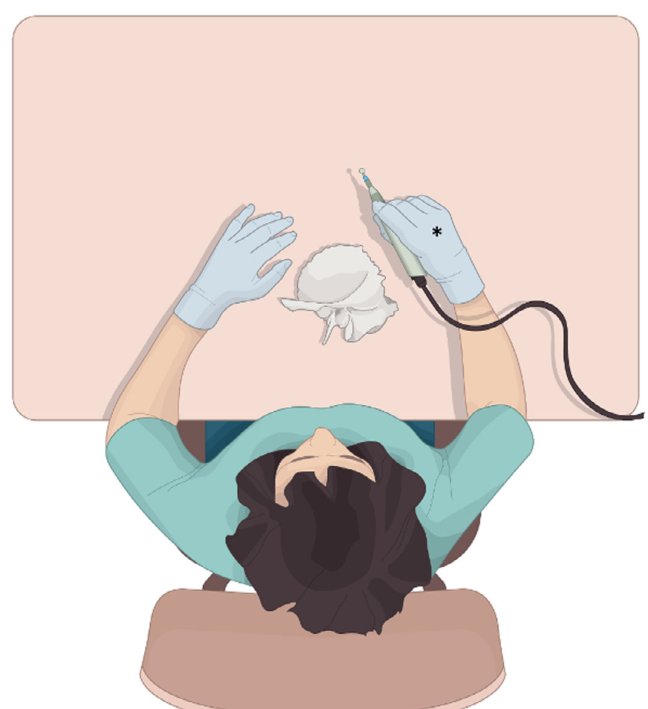

Fig. 2. Eagle's eye view of the setup for soft-tissue work and cochlear electrode insertion. * = placement of Inertial Measurement Unit (IMU) after the soft-tissue work was completed. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

Straight electrode, Cochlear Limited, Sydney, Australia) using forceps. Surgeons were instructed to provide verbal cues as follows: (1) "start" before starting the insertion of the CI electrode and (2) "stop" upon completing the full insertion of the electrode array into the cochlea. The experimenter started and stopped data collection in response to these verbal cues. Each participant performed three trials using cadaveric temporal bones, yielding data from nine separate cochlear electrode insertions.

Data Analysis

The IMU measures the acceleration of the hand in three coordinate directions (ax, ay, az). The raw acceleration data from IMUs can have the following issues (1) small variations in the sampling frequency, (2) intermittent missing data values (approximately 2.5% of total time of data collection), and (3) drifts in the acceleration signals; accelerations obtained from IMUs are known to suffer from drift, which lead to non-physiological velocities after the integration of the acceleration. To address the first two issues, the acceleration signal in each coordinate direction was resampled to a uniform 100 Hz frequency using linear interpolation. To address the third point, the resampled data were band-pass filtered using a 6th order, zero lag, Butterworth filter with cutoff frequencies of 1 and 20 Hz. The lower cutoff of the bandpass filter removes the slow drift; this is a typical method to resolve the drift issue in IMU data.[10,11] Finally, to eliminate any motion artifacts associated with starting and stopping the procedure, and any potential mismatches between the "start" and "stop" cues provided by the participant and the actual duration of data collection, the middle 75% of the filtered acceleration signals were isolated for further analysis. Downloading and processing of the data took an average of 60 s. Finally, we evaluated the signal-to-noise ratio (SNR) of the IMUs to ensure accurate motion detection. Noise density was utilized to determine SNR.[12]

The interpolated and filtered signals were integrated to obtain the hand velocity in the three coordinate directions. The initial velocity was assumed to be zero. The hand speed was then computed from the velocities in the three directions using the Pythagorean theorem. The time series for the hand speed was obtained for all nine trials. From these time series, the outcome measures were obtained, namely, the mean and the variance of the speed, and the peak speed for the trial. Across-trial summary statistics were computed for these outcome measures for each participant. To determine whether there was a difference in mean speed across trials within surgeons, a mixed regression model was utilized in Statistical Package for the Social Sciences (SPSS, version 28). Statistical significance was deemed $p < 0.05$.

RESULTS

The surgeons did not report any discomfort due to the placement of the IMU on their hand. Surgeon A has been a practicing general otolaryngologist with 8 years of experience at a tertiary academic center performing an average of 10 cochlear implants per year. Surgeon B is a fellowship trained neurotologist with 14 years of experience at a tertiary academic center who performs more than 50 cochlear implants per year. Similarly, surgeon C is a fellowship-trained neurotologist with 10 years of experience practicing at a tertiary academic center who performs more than 50 cochlear implants per year.

Table I, provides the mean ± SD speed recorded per trial, and Table II summarizes the three-trial mean ± SD for the three surgeons. The highest mean speed was 8.4 ± 1.7 mm/s (Surgeon B), and the lowest mean speed was 1.9 ± 0.9 mm/s (Surgeon C). When comparing means across trials within the same surgeon, there was no statistical difference ($p > 0.05$). Based on Table I, variance across trials in the form of standard deviation progressively decreased. Table III provides the peak speed recorded per trial and the mean ± SD maximum speed across all three trials.

Figure 3 shows the speed data from all nine trials obtained from the three participating surgeons. The data reveal the difference between the performance of the three surgeons. Note that the scales on the X and Y axes of the three subplots are identical. The time taken by the three surgeons for the procedure—which required the same displacement of the electrode array—ranges from 3.6 seconds (Surgeon B, Trial 2) to 68.8 s (Surgeon C, Trial 1). This difference is reflected in the average speeds; the speed of the shortest-lasting trial is high (8.4 ± 1.7). However, this information is perhaps not as apparent in the across-trial average speed for Surgeon 2 (Table II). The figure also reveals brief bursts of high speed (Surgeon A, Trial 1 and Surgeon B, Trial 1).

We evaluated the signal-to-noise ratio (SNR) of the IMUs to ensure accurate motion detection. The manufacturer specifies a noise density of 180 μg/√Hz (where $1\ g = 9.8\ m/s^2$), resulting in total noise levels of 805 μg (or 0.805 mg) root mean square (RMS) for a 20 Hz bandwidth and 180 μg (0.18 mg) RMS for a 1 Hz bandwidth. Using the data from the surgeon with the lowest

Table II.
Across-trial mean speed for each surgeon.

Participant	Three-Trial mean ± SD speed (mm/s)
Surgeon A	3.5 ± 1.9
Surgeon B	4.7 ± 2.8
Surgeon C	2.2 ± 0.9

Table I.
Mean speed per trial for each surgeon.

Participant	Trial 1 mean ± SD speed (mm/s)	Trial 2 mean ± SD speed (mm/s)	Trial 3 mean ± SD speed (mm/s)	*p* value
Surgeon A	3.8 ± 2.1	4.5 ± 1.6	2.2 ± 0.9	0.42
Surgeon B	2.5 ± 2.1	8.4 ± 1.7	3.1 ± 1.31	0.15
Surgeon C	2.4 ± 1.0	1.9 ± 0.9	2.1 ± 0.7	0.61

Participant	Trial 1 Peak Speed (mm/s)	Trial 2 Peak Speed (mm/s)	Trial 3 Peak Speed (mm/s)	Three-Trial mean ± SD peak speed
Surgeon A	22.5	13.2	7.6	14.4 ± 7.5
Surgeon B	17.9	14.0	7.7	13.2 ± 5.2
Surgeon C	7.3	6.8	6.4	6.8 ± 0.5

Table III.
Peak speed recorded per trial, and the mean ± SD maximum speed across three trials.

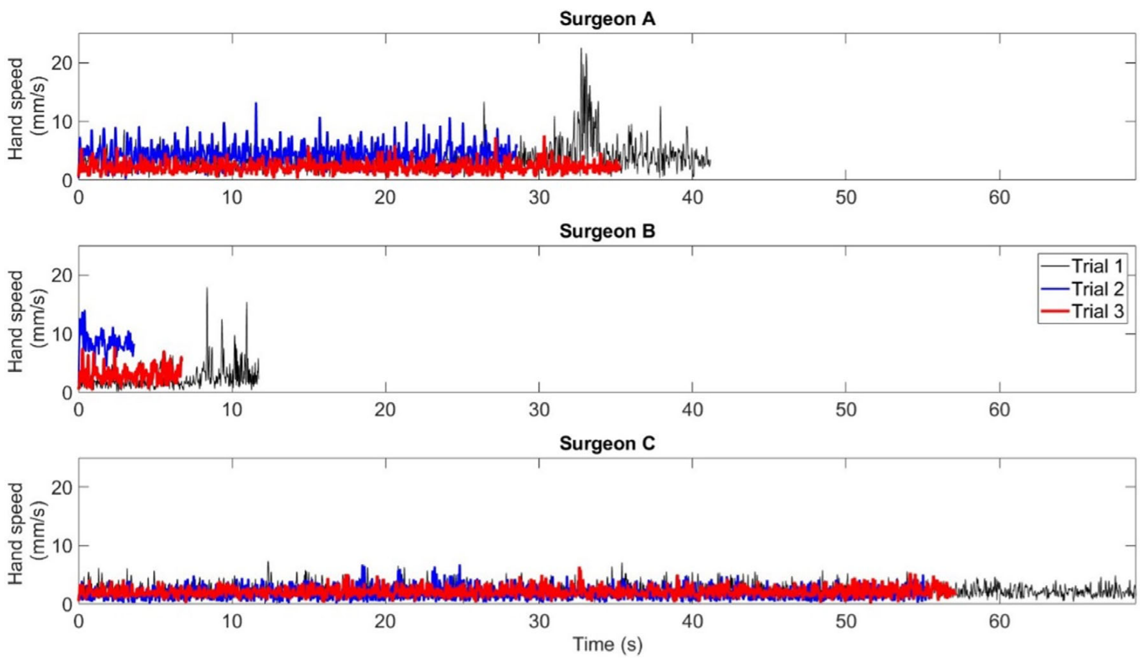

Fig. 3. Speed as a function of time from all nine trials. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

insertional velocities (Surgeon C), we can obtain an RMS of 34.5 mg, 67.7 mg, and 30.7 mg for the X, Y, and Z axis of the accelerometer which lie well above the value of 0.850 mg specified by the manufacturer, indicating a high SNR. Consequently, the signals captured were well above the noise floor, allowing for reasonable data interpretation without concerns of noise interference.

DISCUSSION

Principal Findings and Correlates with Literature

In this study, we prototyped IMUs in the cadaveric temporal lab to provide hand kinematic information while inserting CI electrode arrays. We obtained three variables that may be of interest for OHNS training: (i) mean insertional speed, (ii) peak insertional speed, and (iii) variance in speed as a function of time. A number of studies have shown the effect of mean insertional speed on intracochlear integrity,[2,3,13] which highlights the importance of training with specific regard to this variable. The mechanism behind intracochlear injury is related to increased hydraulic pressure due to displacement of the perilymph.[14] High speeds prevent perilymph egress from the cochlea thereby causing increased pressure, causing damage to neighboring structures. Previous studies have demonstrated the cochlea's susceptibility to trauma when exposed to forces, with injury threshold cited between 0.026 and 0.042 Newton.[15] For reference, manual insertion speeds of 1.33 mm/s can generate 0.32 Newton of force with higher speeds showing a positive correlation with higher intracochlear forces.[5] In our feasibility study, we used the speed obtained from an IMU placed on the dorsal aspect of the hand as a surrogate for electrode array insertional speed. We obtained higher insertion speeds (Tables I and II) compared with the speed range (0.7–2.8 mm/s) reported by others.[5] The difference may be because we obtained data from the back of the hand rather than directly from the electrode array. Though this study was not purposed to evaluate the effect of repetition on insertional velocity, we examined whether there was a significant difference in mean insertional speed across trials. The analysis did not yield statistical significance, which may be expected in the motions of experienced surgeons. However, the effect of repetition on velocity may be apparent when our methods are perfected and employed for training. This will be the goal of future studies.

Peak speed is another variable of interest during training given the direct correlation between speed and forces as previously discussed. Given the proportional relation between speed and intracochlear hydraulic pressure, the most significant intracochlear forces occur when the insertion speed is high. Therefore, peak speed is a relevant variable to minimize during training. Note that small durations of high speed in a long time series will have small impact on the mean and the standard deviation of the entire time series. For example, Surgeon B demonstrated the highest standard deviation in insertion speed (2.9 mm/s; Table III). However, Surgeon A demonstrated the highest peak speed (22.5 mm/s; Table III). This suggests that focusing only on mean and standard deviation of the speed may result in unrecognized potential intracochlear damage from high speeds.

The time series of the insertion speed supports this idea. Figure 3 shows periods of bursts in speed which can be related to multiple factors including changes in intracochlear anatomy[16] and variable electrode trajectory.[17] The amplitude and incidence of these bursts provide insight into variability. Recurrent transient periods of high speed, as is the case with non-continuous insertion of the electrode array, generate spikes in hydraulic pressure similar to loud sound exposure associated with hair cell loss.[14] Therefore, minimizing the incidence of these spikes may be of interest for OHNS training. These spikes can be minimized by refining surgical techniques involving the electrode trajectory. When the electrode orientation is consistently angled toward the modiolus, the force acting against the electrode is small because the electrode does not contact the cochlear walls.[17] This means that the surgeon can insert the electrode with less effort. Conversely, when the orientation is improper, the electrode comes into contact with the cochlear wall, leading to increased resistance. Albeit speculative, the electrode may lose contact with the wall which may instantaneous high speeds, like those observed in Figure 3. Therefore, the local bursts of speed may reflect a higher potential for injury risk through two mechanisms: the increased shear force on the electrode when it pushes directly against the cochlear wall may lead to damage, and the increased pressure that would result from the subsequent high speed.

Considerations of Implementing IMUs

In this study, we computed the vector sum velocity rather than using individual axis because this allows us to ignore changes in the IMU orientation. By these means, we can compare performance across tests since the orientation of the IMU does not have to be aligned to a cardinal axis, thus improving the repeatability of using the IMUs within and across trials.[18] Because the IMU was placed on the hand rather than the electrode, isolating the velocity vector that corresponds to the displacement along the scala tympani would require accounting for the orientation of the hand relative to the electrode. This can be done using two IMUs, one on the hand and one on the electrode. However, a better solution is to use smaller IMUs that are placed directly on the electrode; signals from this IMU would provide direct measurement of the electrode insertion speed. Several compact IMUs on the market, measuring 3 x 3 x 1 mm[12,19] or 0.8 x 2.5 x 3 mm[20], offer suitable alternatives.

The accuracy of IMUs enabled the quantification of tremors,[21] which has both positive and negative aspects. On the positive side, it demonstrates the ability of IMUs to detect small movements. On the negative side, these are motion artifacts that are included in our data. We decided to retain the components associated with tremor (4–12 Hz[22]) to demonstrate the measurement capability of the IMUs; these can be removed using a more aggressive filter with a higher low-pass cutoff. However, as we suggest above, this should not be an issue in future work where smaller IMUs with similar measurement sensitivity will be placed on the electrode rather than the hand.

The IMUs utilized in this study exhibited a strong SNR enabling us to accurately detect low accelerations. Although the SNR of the IMUs assures confidence in the significance of the data, there are limitations in our data analysis approach. Because we are using acceleration to find velocity, perfectly smooth periods characterized by zero acceleration would result in reported velocities of zero. This may not be the case for inexperienced surgeons who are at the beginning of their training; however, it could be an issue with more seasoned surgeons. Future studies using smaller IMUs attached directly to the electrode will be needed to fully assess the true impact of these events on our data analysis approach.

Despite the accuracy of IMUs during low accelerations, the IMU data output should be validated against a gold standard such as an optical motion capture system such as the one employed by Kesler et al.[23] Unfortunately, we did not have access to such an optical system. We have demonstrated the feasibility of the approach and further validation with motion captured system could be performed.

Acquiring procedural or motor skills requires repetition and feedback. Multiple educational models for CI surgery have been developed with this framework in mind. Copson et al. developed a virtual reality (VR) based simulation training for posterior tympanotomy, an important step in CI surgery that precedes the insertion of the CI electrode through the round window.[24] Nevertheless, the system they developed does not include training for inserting a CI electrode array. In a recent randomized-controlled trial, however, Frendø et al. expanded the scope of a VR-based training modules to include CI electrodes.[25] In addition, several companies and academic centers have developed VR software for training of temporal bone procedures including cochlear implant surgery.[26–28] VR training can be supplemented with 3D-printed models to provide haptic feedback, thereby enhancing the educational value of these technologies.[29] These are good alternatives to traditional cadaveric temporal training.

Ultimately, the introduction of a new technology into academic settings such as temporal labs requires due consideration for scalability and cost of providing the technology. Many of the disruptive technologies (e.g., virtual reality) in the surgical domain involve substantial investments,[30] which goes beyond the simple acquisition of the devices in that it includes licensing fees, proprietary hand-tracking algorithms, and cost of replacement when the device breaks. Though the use of IMUs requires a tablet and at least one IMU, this system is relatively low cost. There are no licensing fees to operate any of the hardware/software and the IMU can be inexpensively replaced if it breaks. The software required to analyze the data can be implemented on open-source software like Python. Though the IMU + tablet system is comparatively cheaper to VR setups, the IMU system does rely on a functional cadaveric lab, which can be very costly. The goal of this study was to minimize disruption of standard practice. Now that we have demonstrated the feasibility of this concept, future research should measure velocity directly from the electrode by using smaller IMUs such as the ones listed above. Similarly, future research can focus on validation and the development of integrated systems (e.g., combining IMUs with 3D-printed temporal bones).

With robotics-assisted CI electrode array insertion rapidly emerging, the argument against dedicated training can be made. Certainly, there is a growing body of scientific literature showing that the degree of intracochlear pressure observed in robot-assisted surgery is significantly lower when compared to manual insertion.[31] Similar patterns can be observed regarding force variability[32] and peak forces.[33] For comparison, Zuniga et al. performed robotics-assisted CI electrode insertion and achieved low consistent speeds of 0.03 mm/s,[34] which is about 10 times lower than the lowest insertional speeds in our study. Notwithstanding the technological advancements, Lawrie et al. have identified several barriers to implementation of robotics-assisted surgery in the operating room (OR) that may apply to CI surgery including reliance on industry for training provision and equipment maintenance costs.[35] Though not discussed by Lawrie et al., the prevalence of device failures resulting in conversion of surgically-assisted surgeries to manual procedures is another barrier that can be seen in other surgical specialties.[36] Training OHNS residents with specific regard for lower insertional speeds may allow residents to limit intracochlear trauma regardless of the presence of these barriers.

It is important to acknowledge limitations regarding the implementation of IMUs in the temporal lab. Firstly, the development of the software to analyze the data can be challenging without a background in coding. Secondly, perfusion of the cochlea with perilymphatic fluid, a variable known to impact degree of shear forces encountered within the cochlea, is absent in cadaveric temporal bones.[37] This can affect the replicability of outcomes in live surgeries. Lastly, awareness of being observed or tracked (i.e., observer effect) could have influenced the surgeon's behavior, potentially altering the natural way the procedure was being performed.

Future Direction

Although the present study presents IMUs as a feasible option to assess hand kinematics during cochlear insertion, future studies should focus on randomized-controlled trials to assess whether IMU-coupled cadaveric temporal bone training is more effective at training residents in this delicate procedure. A more robust study would also take into account the incidence of basilar membrane disruption as a function of IMU-coupled cadaveric training. With the advent of systems with nerve response telemetry, which provide real-time estimates of EA insertion speed, future studies can explore direct comparisons between these systems and IMUs.[38] Specifically, a focus could be placed on comparing average values, as the primary metric provided by the system is the average insertion speed.[38]

Implications for Practice

This study demonstrates the feasibility of employing inertial measurement units (IMUs) in cadaveric temporal bone laboratories for objective quantification of insertion speed during cochlear implant surgery resident training. With objective kinematic data, novel resident performance metrics that may correlate with traumatic surgical outcomes can be explored. The potential utility of IMU-derived performance metrics as resident feedback during training is promising, and their affordability and ease of use suggest broad scalability of this approach.

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