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Project Title: **Evaluation of Printed 3-Dimensional Temporal Bone Models in Surgical Procedures**

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Summary (250 words max single spaced):

Background: The current surgical training model is based primarily on cadaveric dissection; however, opportunities are limited due to small numbers of specimens. Alternatives to cadaveric dissection such as virtual reality simulations and rapid prototyped models attempt to replicate the cadaveric gold standard in order to enhance the learning process. Cadaveric comparison to virtual haptic modeling, as undertaken in Australia, demonstrated significant differences in drilling techniques based on hand motion analysis. This raises concerns that some forms of simulation may result in the development of inappropriate and maladaptive skills.

Objective: To determine if there is a significant difference in drilling technique during surgical training procedures on rapid prototyped 3D temporal bone models and cadaveric specimens.

Methods: Eight (8) otolaryngology residents completed a mastoidectomy on cadaveric temporal bone and printed models. Motion sensors within an electromagnetic field were used to capture drilling technique.

Results: Significant differences in the drilling technique was demonstrated. An increased number of curved strokes, and longer, faster strokes were taken when drilling the printed models. It was also noted that junior residents had significantly different drilling technique when compared to the senior residents.

Conclusion: Technique growth from junior to senior level residents was shown to occur. Therefore, caution must be taken when residents drill printed models because results demonstrate altered drilling technique.

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Introduction

The classical apprenticeship model for resident surgeons is focused on the need for experience in order to gain insight and refine surgical skills – “the more you do, the more you know”[1]. Cadaveric temporal bone dissection has traditionally be the golden standard of surgical training in otolaryngology[1–3]. However, learning opportunities are limited due to the small number of cadaveric specimens available. The development and use of technologies such as virtual reality, simulators, haptic models and rapid prototyped models may provide additional opportunities that are more readily accessible[4–9]. Factors such as fidelity of temporal bone anatomy and the ability to recreate a realistic experience with these models is key for proper training[1,10,11]. Both haptic and rapid prototyped models have been shown to be capable of high levels of anatomical fidelity, while the realism of drilling has been difficult to objectively quantify[5,7,12,13].

A study out of Australia illustrated significant differences in the drilling technique between a high fidelity virtual reality simulation and cadaveric samples[12]. This raises concern that while anatomical fidelity can provide important learning scenarios, reinforcement of incorrect drill handling techniques may occur. Examining a different modality, this study compares resident hand motions produced during a mastoidectomy with posterior tympanotomy of cadaveric specimen to a rapid-prototyped 3D-printed model. The Laboratory for Surgical Modeling, Simulation and Robotics has developed a rapid prototype printing method based on microCT data and uses specific materials that mimic bone[7]. Determining the similarities between 3D printed and cadaveric models will determine the potential for application of the printed bone. Models that teach accurate drilling technique alongside anatomical correctness can be used to supplement cadaveric specimen. With differences present between the modalities, caution must be used in order to prevent maladaptive skills from manifesting during the training process.

Background

Current Training Model

Cadaveric dissection has long been the gold standard for surgical training alongside the ‘see one, do one, teach one’ motto [1,3,10]. However, due to limited volume, legal regulation and safety, it can be difficult to accumulate sufficient hours in order to maintain skills, practice new technique or subspecialize[1,3,10]. Some suggest shifting from repetition-based time and volume training, towards competency based training which would require standardized methods of assessment not possible with cadaveric specimen[2,3]. The use of cadaveric specimens will always remain essential to learning temporal bone anatomy and surgical technique, but the development of new modalities for surgical resident training opens the doors for built-in feedback, standardization and deliberate practice[1–3].

Alternatives to Cadaveric Dissection

There are numerous training modalities with varying levels of fidelity and realism, such as virtual simulation and rapid prototype 3-dimensional physical models. Simulations are the artificial representation of a real world process with the aim to facilitate learning through immersion, reflection, feedback and practice without the risks of real life[8]. The goal of using such technologies is to enable more educational opportunities, maximize patient safety, and allow for assessment and documentation of surgical skills[8,9,14].

The materials that these alternatives are composed of range from plastic, metal, powder based, to porcine; or models may be virtual simulations with no physical model at all[1,4,6,7,15]. The properties of the tangible models are dependent on the materials in which they are made of and the printing techniques employed – thus it must be noted that not all rapid prototype 3-dimensional models will reflect the same behaviours. Many of these alternatives to cadaveric dissection have been well documented; nevertheless, cadaveric dissection remains the set standard for comparison.

Each model or simulation has unique advantages and disadvantages. A method such as selective laser sintering - which is based on small particles of thermoplastic, metal, ceramic or glass that are fused together by a high power laser - is not only expensive, time intensive production, but rougher and less detailed, thus limiting it's use[16,17]. Stereolithography, or 3-dimensional printing, is the most common rapid prototyping method. It creates stacks of data slices that can be created as a solid product using liquid, solid or powder based materials[16]. Accurate reproduction of internal structures with printed models has been hindered by the need for support structures and the retention of internal material[4,7,16]. However, techniques have been developed to circumvent this and anatomical fidelity in some models has been validated[4,7]. Haptic models utilize motors and gears to implement a force feedback system allowing tactile interaction side by side with visual renderings on a computer[9,12]. The force feedback system doesn't allow for torsional force and may limit the magnitude that is encountered in reality[12].

Hand Motion Analysis

Hand motion analysis uses an electromagnetic field to track sensors and capture motion data[12,18]. Based on the data collected, various metrics such as time taken to complete a procedure, number of strokes, path of the dominant hand, acceleration and velocity have all been used to quantify drilling technique[18–20]. Using hand motion analysis allows skill to be measured quantitatively by relating it to the subject's dexterity and technique[12,18]. A study by Datta et al. was able to demonstrate, via hand motion analysis, that surgical trainees with better manual dexterity scored higher outcome measures[11,21].

Virtual Reality Simulation in Comparison to Cadaveric Hand Motions

A study by Ioannou et al., hand motion analysis was used to compare high fidelity virtual reality simulation to cadaveric specimen during simulated mastoidectomy and cochleostomy to determine if expert behaviour changes with the different environments[12]. The virtual reality simulations presented 3D renderings of temporal bone that can be operated on with haptic devices to simulate the drill. Five (5) experts otologists completed the simulation with cadaveric bone mounted to replicate the standard patient operative position[12]. Hand motions were captured using a sensor placed directly on the drill. The results of this study yielded a significant difference in hand motions during temporal bone surgery between these modalities. Within the simulator environment, drilling strokes were significantly different across most stages and exhibited different patterns. More straight strokes and fewer rounded strokes were recorded when compared to the results of cadaver drilling[12]. The study concluded that drilling between the two environments was not identical and trainees should have an existing frame of reference from cadaver-based training so as not to develop maladaptive techniques.

Objective

To determine if there is a significant difference in drilling technique when comparing hand motion during surgical training procedures on rapid prototyped 3-dimensional temporal bone models and cadaveric specimens. This in turn will be contrasted to an external study looking at haptic surgical simulations which has previously shown significant differences.

Materials and Methods

Study Participants

The study was comprised of eight (8) otolaryngology residents; five (5) junior residents, defined as those in their first through third year of training, alongside three (3) senior residents. All participants were right handed. Approval was granted by the Health Research Ethics Board at the University of Manitoba prior to commencement of obtaining data, as well as consent obtained from each individual.

Cadaveric Bone and Rapid Prototyped Material

Hand motion behaviour was monitored over the course of drilling temporal bone of two different materials. The first material was traditional cadaveric bone collected as per standard University of Manitoba protocols. The second material was a rapid prototyped model developed internally by the Laboratory for Surgical Modeling, Simulation and Robotics. The printing process is as described by Hochman et al. and produces a 3-dimensional model with internal and external anatomical fidelity based on a microCT scan of temporal bone [7]. Participants were allocated to either a cadaveric or a printed model for drilling, with some participants partaking in crossover sessions doing both cadaveric and printed.

Drilling Procedure

Both the cadaveric and printed models were mounted in a bowl-type holder to mimic the surgical approach to temporal bone in a live patient, and also to maximize the realism and maintain a level of consistency. Each participant was asked to identify three (3) different but well-defined stages while drilling: cortical mastoidectomy, thinning procedures including posterior canal wall thinning, drilling along the dural plate and sigmoid sinus, and drilling of a facial recess[12,22]. These divisions were created to separate the different techniques used throughout temporal bone surgery[22].

Hand Motion Devices

Hand motions were captured using the Ascension TrakSTAR system with four (4) motion sensors[23]. Sensors are tracked simultaneously in six (6) degrees of freedom within an electromagnetic field created by a mid-range electromagnetic transmitter[23]. Coordinates on a Cartesian plane, as well as orientation measures such as azimuth, elevation and roll are recorded by this system. The accuracy of the TrakSTAR system is 1.4mm RMS or 0.5 degrees RMS and has a user-configurable measurement rate[23].

The larger 8mm sensors were placed on the bowl-type holder containing the mounted bone or model, and on the drill shaft; while smaller 2mm diameter sensors were placed on the participants' wrist just below the radial styloid process, and a fourth was placed above the first metacarpophalangeal joint or mid-thumb as seen in Figure 1. The small size of the sensors ensured that their attachment did not hinder or alter trainees' activities. The set-up can be seen in Figure 2.

The data collected from the sensors is displayed in real-time and recorded for later analysis using the software package Cubes™. Data was recorded in timed sections of five (5) minutes or less in order to decrease the recording of large repositioning movements and other movement unrelated to drilling technique. Scenarios leading to less than the allocated five (5) minutes included when a participant indicated the completion of a surgical segment, equipment adjustment or needed to pause to ask the supervising attending a question.

Figure 1: Sensor attachment for dominant hand.

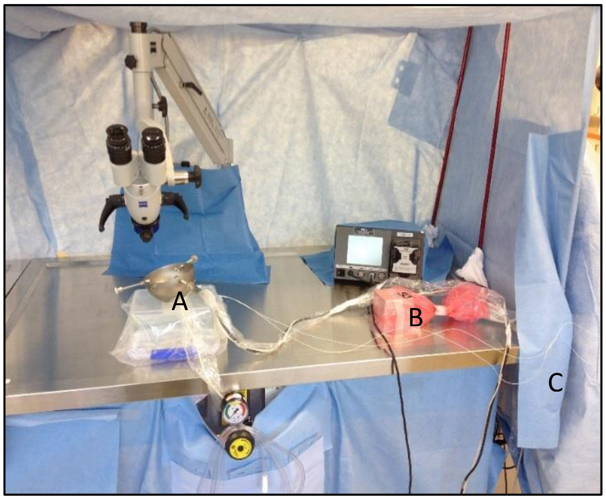


Figure 2: Drilling set-up. (A) Bowl-type holder (B) Transmitter for Acsension TrakSTAR system (C) Cables for sensors

Software and Calibration

All analysis software was developed internally through the Laboratory for Surgical Modeling, Simulation and Robotics at the University of Manitoba. Preliminary analysis was done using Motion Analysis and Recording Systems (MARS) software which converts x, y, and z position values into dynamic metrics such as velocity and acceleration. These metrics can then be used to define recorded motions as individual strokes based on filters and thresholds allowing for objective comparison between the cadaveric bone and printed models.

MARS uses a Gaussian filter in an attempt to eliminate background noise; however, it must be noted that there is no low pass filter that will entirely remove unwanted noise[18]. Therefore, additional thresholds can be set to further limit what is considered a meaningful movement made by the participant in a secondary attempt to limit hand tremor, drill vibrations and experimental error. A high and low threshold for each metric was chosen based on previously validated values. Also, a predetermined calibration set of movements was used, so that recorded strokes could be correlated with a known number of hand motions to ensure proper capture by the software[18,20].

When using velocity to define a stroke, a change of velocity greater than 5mm/s was required at the low threshold, while 15 mm/s was required for the higher threshold. By using velocity as a measure, both direction and speed are taken into account. When using acceleration to define a stroke, an acceleration of 2 mm/s^2 was required at low threshold, while an acceleration of 5 mm/s^2 was required for the higher threshold. Lower thresholds were chosen in order to capture finer movements; however, the lower the threshold, the greater the amount of noise that will pass. Increasing the threshold to the higher value decreases the amount of noise significantly but there is a loss of the finer motions and may capture an incomplete picture. For this reason both thresholds were taken into consideration during data analysis.

Further analysis was done using a second piece of internally developed software that uses a cosine (k-cos) function to detect changes in direction in order to identify strokes[24]. This method of analysis parallels the analysis Ioannou et al. completed using cadaveric and haptic models[12,24]. Using this k-cos function a stroke is determined based on directional change or the curvature within a frame of data points. A moving frame of 10 data points was examined, using an angle of less than 120 degrees to parse individual strokes.

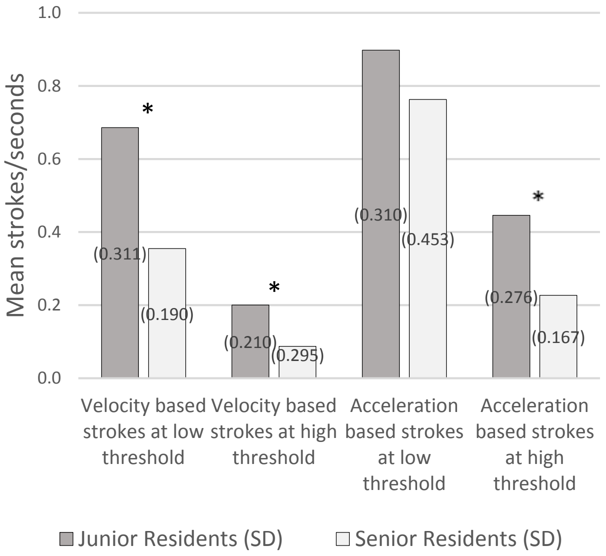
A frame rate-independent low pass smoothing filter was applied four (4) times in order to eliminate vibrations from the drill, hand tremor and experimental error as much as possible[25]. A series of calibration trials using the same predetermined set of movements as with the MARS software, were done so that hand motion analysis was appropriately matched to the manually counted number of movements. The calibration trails took into consideration length of stroke, direction and speed of the movements that would be expected in a mastoidectomy.

Data Analysis and Results

MARS Preliminary Analysis

The results returned from MARS were initially grouped based on junior and senior levels to determine if there was a difference in the drilling methods of residents at different stages of training. Figure 3 and Figure 4 show the comparison of junior to senior residents across various categories using a t-test to compare mean values. It can be seen that in all cases of significant differences, junior residents had an increased number of strokes per second. This comparison was tested in order to validate the experiment as one would expect to see a difference in drill technique with skill development and refinement occurring over the course of training. Results from junior and senior residents were combined to allow sufficient data points, while recognizing that this may affect final results. Figure 5: Comparison of mean strokes per second with strokes determined via (A) low threshold velocity, (B) high threshold velocity, (C) low threshold acceleration and (D) high threshold acceleration. Three (3) drilling segments observed were (i) cortical mastoidectomy, (ii) thinning procedures and (iii) facial recess.Figure 5 shows the results of t-tests comparing results from drilling cadaveric bone with the mean strokes made per second of the same procedure on 3D printed models. The most significant differences were noted during the thinning procedures.

Since the objective is to determine drilling patterns during temporal bone surgery, the data from the drill sensor was of most interest with it being closest to the point of contact between the drill bit and the specimen. **Error! Reference source not found.** and **Error! Reference source not found.** found in the appendix contain additional results from the thumb sensor. Due to multiple hypotheses being tested from the same data, a Bonferroni correction was applied and significant results were considered with a p value of 0.017.



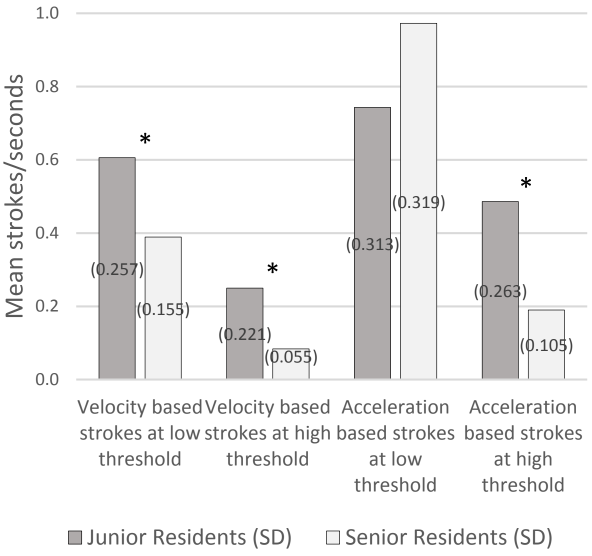


*Figure 4: Comparison of mean strokes per second from junior vs. senior residents based on data collected via sensor on drill shaft during the cortical mastoidectomy. *Significant p values seen for velocity based strokes as both low (p = 0.001) and high (p = 0.003) threshold as well as acceleration based strokes at high threshold (p = 0.012).*

Figure 3: Comparison of mean strokes per second from junior with senior residents based on data collected via sensor on drill shaft during thinning procedures. Significant p values see for velocity based strokes with both at low (p = 0.002) and high (p = 3.00 x 10^{-4}) threshold, as well as acceleration based strokes at a high threshold (p = 5.50 x10^{-5}).

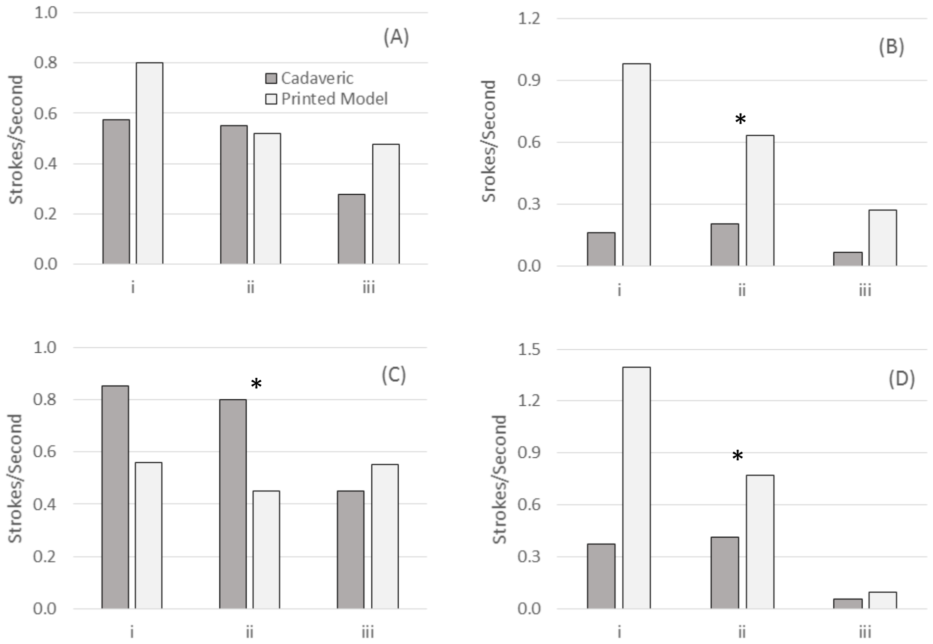


Figure 5: Comparison of mean strokes per second with strokes determined via (A) low threshold velocity, (B) high threshold velocity, (C) low threshold acceleration and (D) high threshold acceleration. Three (3) drilling segments observed were (i) cortical mastoidectomy, (ii) thinning procedures and (iii) facial recess. Those pairs demonstrating a significant p value are: velocity determined strokes at a high threshold during thinning procedures (p = 3.2 x 10^{-5}), and acceleration determined strokes at low (p = 1.1 x 10^{-5}) and high (2.2 x 10^{-5}) threshold for thinning procedures. See Table 1: Preliminary analysis using MARS comparing mean strokes/second (mm/s) between junior and senior residents when drilling cadaveric bone.

K-Metric Analysis

The k-cos software provided a greater ability to compare additional metrics such as ratio of straight strokes to curved strokes, individual stroke lengths, and time per stroke. The k-cos method has previously been used in other studies, such as that by Ioannou et al., and by adding it to this study are able to reasonably compare our results to others[12,24]. Due to the small sample size used in this study, it is expected that differences in outcomes between MARS and k-cos methods might be seen; however, these differences would likely be eliminated with increased participants and trials.

In comparing junior with senior residents using this software significant differences can be seen throughout the different metrics analyzed. T-tests were done using the mean for each group when looking at each hypothesis. Results are shown in Figure 6 and Figure 7 and a tabulated version of the data is in Table 4 in the Appendix. Due to multiple hypothesis within the same set of data a value of 0.013 after Bonferroni correction is considered significant. Results indicate that once again there is a difference between the technique of junior and senior residents. Junior residents appear to take a greater number of shorter strokes during thinning procedures, as well as consistently using more curved strokes throughout the entire drilling session.

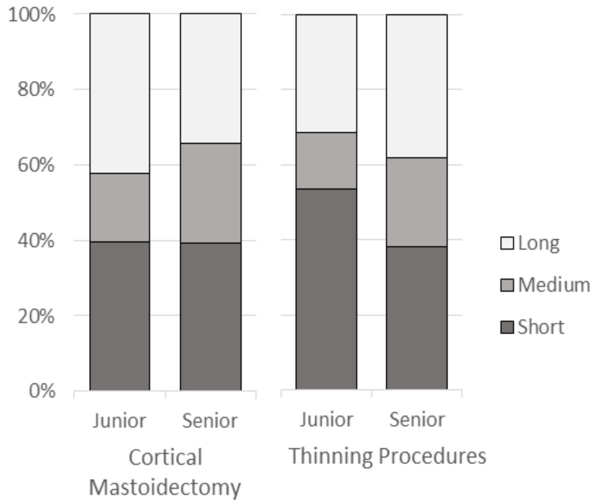


Figure 7: Ratio of short, medium and long strokes made by junior compared to senior residents. Significance (p = 0.008) was noted with short strokes during thinning procedures.

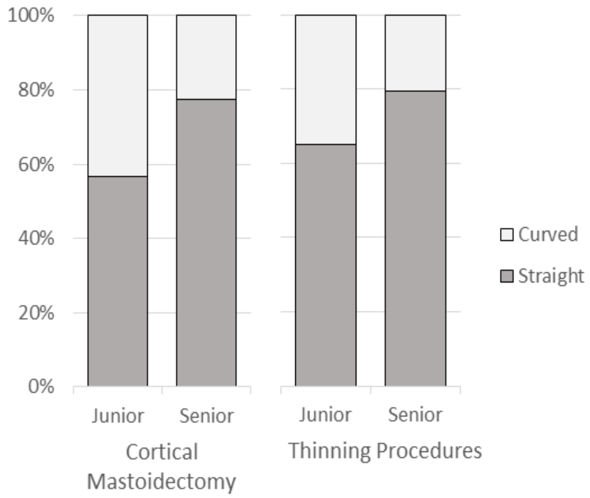


Figure 6: Comparison of junior vs senior ratios of straight to curved strokes. All t-tests returned significant p values between junior and senior residents drilling technique.

A comparison of mean strokes per second was also completed with the k-cos analysis method. Results are as seen in Figure 8. Based on this analysis there were no significant differences between the cadaveric and printed model based on the sensor attached to the drill.

Ioannou et al. found their most significant difference when examining the types of strokes made between cadaveric and haptic, showing that more straight strokes were used during a haptic simulation[12]. Figure 9 shows the ratio of straight to curved strokes captured when drilling cadaveric bone versus 3D printed models and shows the opposite effect – greater use of curved strokes when drilling the printed models. Significance was shown in all drilling segments from the drill sensor.

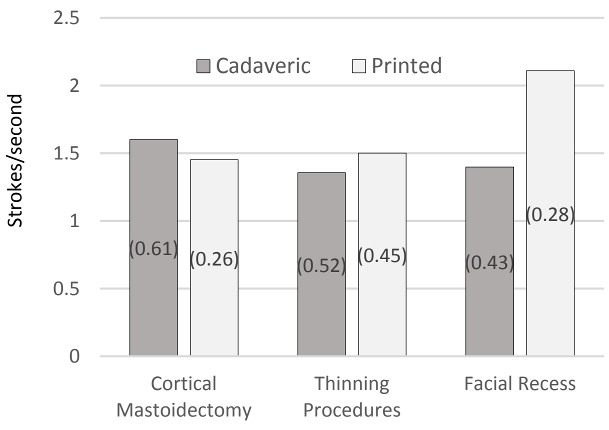


Figure 8: Comparison of stokes per second using k-metric analysis for cadaveric bone versus 3D printed models.

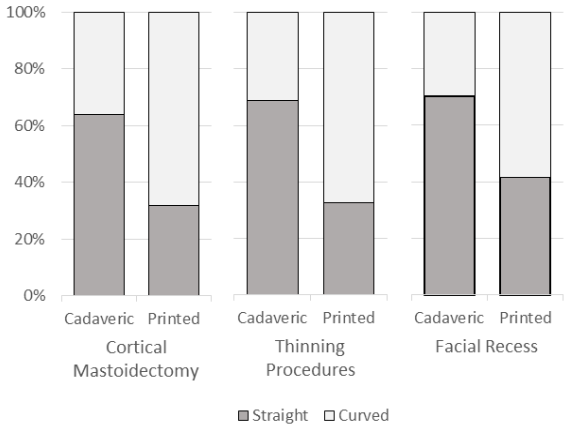


Figure 9: Ratio of straight versus curved strokes for cadaveric and printed in three drilling segments. Significant p values were seen in all comparisons of cadaveric to printed results, values found in Table [] in the Appendix.

A second ratio that was compared was that of the length of strokes made. Short strokes were considered as less than 5mm, medium length stroke was greater than 5mm but less than 10mm, and a long stroke is anything greater than 10mm. Significant differences were found in the cortical mastoidectomy and thinning procedures with respect to short and long strokes.

The final comparison examined was mean stroke duration, results seen in Figure 11. This shows that throughout all drilling segments strokes tended to be faster with using the printed models, with 50% less time being taken per stroke.

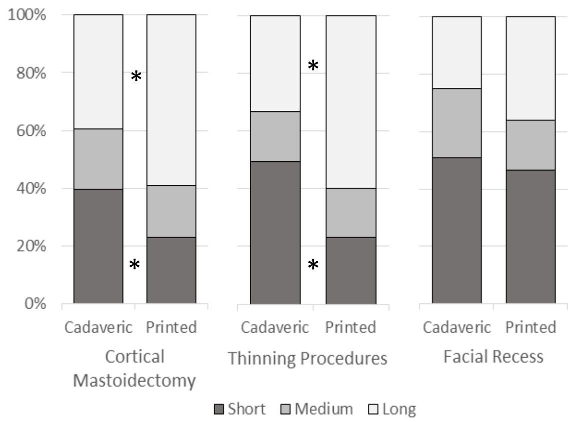


Figure 10: Ratio of short (<5 mm) to medium (5 < x < 10 mm) to long strokes (>10mm) for cadaveric compared to printed models for three (3) drilling segments. Significance (*) noted in short (p = 0.001) and long (0.004) strokes of the cortical mastoidectomy and short (p = 6.3 x 10^{-7}) and long (p = 2.1 x 10^{-5}) of the thinning procedures.

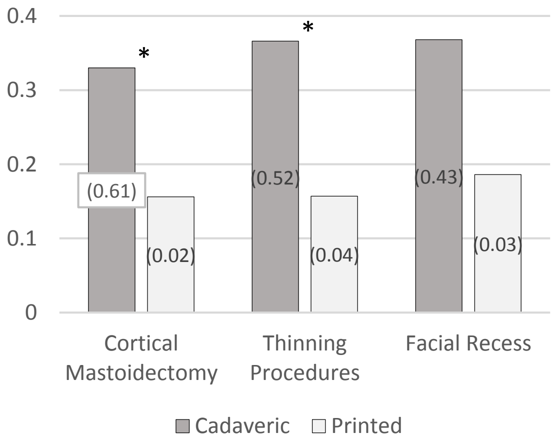


Figure 11: Mean stroke duration comparing cadaveric bone to printed models. Significant p values noted for cortical mastoidectomy (p = 2.8 x 10^{-9}) and thinning procedures (p = 6.2 x 10^{-15}).

Discussion and Recommendations

Comparison of Cadaveric Bone to 3D Printed Models

Based on the analysis of various metrics comparing cadaveric bone to rapid-prototyped 3D-printed models, results showed differences between the two materials. When mean strokes per second were analyzed with MARS software there were a few points of significant difference; however, further analysis was required as there was no consistency with regards to which drilling segment or material type had a higher mean value. When the same metric was analyzed in the k-cos analysis, there were no significant differences found. The discrepancy may be related to the method of analysis or the limited sample size.

A second metric examined was the percent of straight and curved strokes, depicted in Figure 9 as ratios. Significantly more curved strokes were used across all drilling segments when the printed models were used. With regards to the lengths of strokes taken, it was found that the printed models resulted in a greater number of long strokes and fewer short strokes, while medium length strokes remained consistent for both materials. These findings show that residents adapt their drilling technique within each environment.

A final variable taken into consideration was time per stroke. Results show that strokes taken when drilling the printed models were consistently shorter in time. Therefore, the printed model produced not only longer strokes but quicker strokes as well. This may indicate that residents are less cautious when drilling the printed models, that they have adapted to the alternate environment, or a combination of the two.

These differences may be attributed to the mechanical properties of the materials used to make the 3D models, as well as the lack of biological non-bony tissue. Hardness, elasticity, density and other properties of the material all play into drilling properties and how the drill burr removes material[7]. Strokes that are more curved may be a result of material that is more easily removed at equal or lesser pressure compared to cadaveric bone. Because the printed models are strictly a representation of bone, the additional hindrances of soft tissue are lost therefore enabling longer, faster strokes. Moisture may also contribute to the difference in techniques, as saline was used to wash the cadaveric bone, while no liquid was used during the printed model drilling to prevent disintegration of the material[26]. These findings indicate areas in the fabrication process of the printed models where alterations may minimize the differences in drilling technique.

Comparison of 3D Printed Models to Haptic Models

The study completed by Ioannou et al. found a number of differences between cadaveric bone and haptic models[12]. Significant results were noted in strokes per second, mean stroke duration, mean stroke distance, and percentages for straight and curved strokes[12]. Using the results from the k-cos analysis the printed models showed differences in many of the same areas, though often of the opposite effect. More straight strokes were used when using the haptic simulation, while more curved strokes were used with the printed model when they are compared to cadaveric drilling. The same effect was also seen with strokes per second and stroke distance. These differences across training models are important to be aware of during the training process in order to prevent maladaptive skills, particularly in junior residents who may not have yet developed a consistent technique. With the current differences to cadaveric bone, neither appears to be an adequate alternative to cadaveric bone training for residents at this time.

Comparison of Junior to Senior Residents

Junior and senior level residents showed significant differences when compared across a number of categories. This indicates that there is indeed a learning process as drilling technique is developed and residents pass from junior to more senior levels. This finding confirmed that the methods of data collection and analysis are valid, as these are the results one would expect. The tools used to teach junior residents need to help teach the correct skills so that they develop the proper technique by the completion of the program. As previous studies recommend, it is crucial that until a certain level of technique has been learned with cadaveric specimen, simulations should not be a primary tool for learning surgical skills in order to prevent maladaptive techniques[4,12].

These results would suggest it preferable to compare junior results amongst other junior results, and similarly with results from senior residents. Due to limited data points it was necessary to combine data to achieve a viable amount of data points within each drilling segment. By combining data in such a manner results may have been skewed in the direction of whichever level of resident is more highly represented in the mixture. Each category contained a different ratio of junior to senior as each participant took different lengths of time within each drilling segment. However, each set of combined results contained at minimum 25% of each to ensure a minimum representation.

Data Collection & Analysis

Analysis of this study focused primarily on the data collected from the sensor attached to the drill shaft. Drilling technique can best be determined based on the drill tip, therefore analysis focused on this sensor. The sensor attached to the thumb was analysed alongside that of the drill and consistently showed similar trends, though to a lesser degree. The reason behind this may be a result of the fact that farther from the drill tip there is less movement and thus becomes more difficult to distinguish a difference in the finer points of drilling technique.

An area of possible error is the thresholds set within the analysis software. There is no certain way to eliminate noise without also cutting out finer movement that was a part of drilling. This may artificially elevate the data from low threshold analysis, while the opposite would be true for higher thresholds. In this particular study, because the data is being compared relative to one another, it would be expected that if noise were present it would be present throughout all samples to a similar degree, thus cancelling each out in the final analysis. However, should absolute values of this study be compared to outside data, discrepancies may be seen for this reason.

Conclusions

Increased curved strokes of longer length and faster speed were seen when residents drilled 3-dimensional printed models compared to the same procedure on cadaveric bone. While these models are a valuable tool in a teaching theatre, caution must be used to prevent maladaptive drilling techniques from forming. Secondary findings showed significant differences between the drilling methods of junior residents compared to their senior counterpart, demonstrating the development of technique from junior resident to senior resident.

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Appendix

Data from MARS Analysis

Table 1: Preliminary analysis using MARS comparing mean strokes/second (mm/s) between junior and senior residents when drilling cadaveric bone.

			Mean strokes/second (mm/s)					
			Cortical Mastoidectomy			Thinning Procedures		
	Sensor	Threshold	Junior (SD)	Senior (SD)	p	Junior (SD)	Senior (SD)	p
Velocity determined strokes	Drill	Low^{+}	0.686 (0.311)	0.355 (0.190)	**0.001**	0.606 (0.257)	0.389 (0.155)	**0.002**
		High^{+}	0.2 (0.210)	0.087 (0.295)	**0.003**	0.250 (0.221)	0.084 (0.055)	**3.0x10^{-4}**
	Thumb	Low	0.103 (0.055)	0.190 (0.095)	0.023	0.199 (0.212)	0.172 (0.071)	0.535
		High	0.016 (0.032)	0.019 (0.032)	0.722	0.018 (0.024)	0.030 (0.045)	0.381
Acceleration determined strokes	Drill	Low^{++}	0.898 (0.310)	0.763 (0.453)	0.410	0.743 (0.313)	0.973 (0.319)	0.055
		High^{++}	0.446 (0.276)	0.227 (0.167)	**0.012**	0.486 (0.263)	0.190 (0.105)	**5.5x10^{-5}**
	Thumb	Low	0.198 (0.105)	0.371 (0.141)	**0.004**	0.326 (0.321)	0.310 (0.152)	0.831
		High	0.054 (0.063)	0.096 (0.095)	0.213	0.080 (0.095)	0.119 (0.145)	0.410

$^{+}$For velocity determined strokes low threshold was a change of 2 mm/s and high threshold was minimum change of 15mm/s.
$^{++}$For acceleration determined strokes low threshold was minimum acceleration of 5 mm/s^{2} and high threshold was 25 mm/s^{2}.

Table 2: Analysis using MARS comparing mean movements per second, based on velocity determined strokes, between cadaveric bone and printed models. Surgical segments are (A) cortical mastoidectomy, (BCD) thinning procedures, and (E) drilling facial recess.

			Comparing mean movements/sec using velocity		
	Threshold	Section	Cadaveric (SD)	Printed (SD)	p
Drill Sensor	Low^{+}	A	0.576 (0.316)	0.801 (0.515)	0.457
		BCD	0.550 (0.253)	0.520 (0.164)	0.591
		E	0.278 (0.192)	0.478 (0.221)	0.188
	High^{+}	A	0.162 (0.182)	0.981 (0.835)	0.146
		BCD	0.208 (0.205)	0.635 (0.298)	**3.2 x 10^{-5}**
		E	0.068 (0.089)	0.273 (0.205)	**0.090**
Thumb Sensor	Low	A	0.132 (0.084)	0.157 (0.105)	0.670
		BCD	0.192 (0.184)	0.204 (0.187)	0.820
		E	0.150 (0.164)	0.374 (0.205)	**0.011**
	High	A	0.017 (0.032)	0.015 (0.032)	0.914
		BCD	0.201 (0.032)	0.029 (0.045)	0.531
		E	0.005 (0.05)	0.092 (0.063)	**0.032**

$^{+}$For velocity determined strokes low threshold was a change of 2 mm/s and high threshold was minimum change of 15mm/s.

Table 3: Analysis using MARS comparing mean movements per second, based on acceleration determined strokes, between cadaveric bone and printed models. Surgical segments are (A) cortical mastoidectomy, (BCD) thinning procedures, and (E) drilling facial recess

			Comparing mean movements/sec using acceleration		
	Threshold	Section	Cadaveric	Printed	p
Drill Sensor	Low^{+}	A	0.853 (0.362)	0.559 (0.241)	0.085
		BCD	0.802 (0.327	0.449 (0.202)	**1.1×10^{-5}**
		E	0.452 (0.374)	0.553 (0.176)	0.646
	High^{+}	A	0.373 (0.265)	1.398 (1.177)	0.181
		BCD	0.410 (0.327)	0.773 (0.239)	**2.2×10^{-5}**
		E	0.054 (0.063)	0.096 (0.095)	0.213
Thumb Sensor	Low	A	0.255 (0.141)	0.210 (0.110)	0.485
		BCD	0.322 (0.285)	0.277 (0.253)	0.558
		E	0.227 (0.202)	0.314 (0.228)	0.565
	High	A	0.068 (0.071)	0.067 (0.114)	0.987
		BCD	0.090 (0.110)	0.122 (0.148)	0.440
		E	0.029 (0.032)	0.161 (0.179)	0.181

$^{+}$For acceleration determined strokes low threshold was minimum acceleration of 5 mm/s^2 and high threshold was 25 mm/s^2.

Tabulated Data from K-metric Analyzed Data

Table 4: Comparison of various metrics between junior and senior residents. Drilling segments: (A) cortical mastoidectomy, (BCD) thinning procedures and (E) drilling of a facial recess.

		Drill Sensor			Thumb Sensor		
		Junior (SD)	Senior (SD)	p	Juniot (SD)	Senior (SD)	p
Strokes/Second	A	1.655 (0.51)	1.495 (0.78)	0.567	1.446 (0.10)	1.561 (0.09)	2.00E-04
	BCD	1.27 (0.49)	1.601 (0.54)	0.093	1.328 (0.41)	1.638 (0.47)	0.068
	All -Cadaveric	1.421 (0.53)	1.535 (0.63)	0.452			
	All - Printed	1.539 (0.57)	1.66 (0.42)	0.603			
% Straight Strokes	A	0.567 (0.07)	0.776 (0.12)	3.00E-04	0.632 (0.10)	0.791 (0.09)	2.00E-04
	BCD	0.651 (0.12)	0.793 (0.07)	5.70E-05	0.646 (0.11)	0.802 (0.10)	0.001
	All -Cadaveric	0.62 (0.11)	0.782 (0.10)	2.80E-08			
	All - Printed	0.355 (0.11)	0.339 (0.08)	0.663			
% Curved Strokes	A	0.433 (0.07)	0.224 (0.12)	3.00E-04	0.368 (0.10)	0.202 (0.08)	0.000
	BCD	0.349 (0.12)	0.207 (0.07)	5.70E-05	0.354 (0.11)	0.198 (0.10)	0.001
	All -Cadaveric	0.38 (0.11)	0.218 (0.10)	2.80E-08			
	All - Printed	0.645 (0.09)	0.661 (0.08)	0.663			
Short Strokes	A	0.394 (0.10)	0.392 (0.12)	0.968	0.728 (0.08)	0.636 (0.12)	0.049
	BCD	0.535 (0.24)	0.382 (0.11)	0.008	0.632 (0.17)	0.646 (0.18)	0.814
	All -Cadaveric	0.482 (0.20)	0.394 (0.11)	0.018			
	All - Printed	0.314 (0.16)	0.262 (0.16)	0.457			
Medium Strokes	A	0.184 (0.05)	0.265 (0.11)	0.047	0.141 (0.04)	0.15 (0.08)	0.763
	BCD	0.15 (0.24)	0.238 (0.11)	0.025	0.154 (0.06)	0.16 (0.10)	0.856

	All -Cadaveric	0.164 (0.06)	0.255 (0.11)	0.001			
	All - Printed	0.172 (0.05)	0.17 (0.05)	0.923			
Long Strokes	A	0.42 (0.10)	0.343 (0.10)	0.048	0.131 (0.06)	0.215 (0.08)	0.011
	BCD	0.315 (0.18)	0.381 (0.17)	0.304	0.214 (0.16)	0.193 (0.13)	0.678
	All -Cadaveric	0.353 (0.16)	0.351 (0.14)	0.948			
	All - Printed	0.502 (0.20)	0.569 (0.18)	0.426			
Time/Stroke	A	0.288 (0.08)	0.414 (0.10)	0.004	0.437 (0.10)	0.467 (0.06)	0.312
	BCD	0.368 (0.11)	0.36 (0.08)	0.786	0.436 (0.13)	0.416 (0.11)	0.620
	All -Cadaveric	0.338 (0.11)	0.385 (0.10)	0.530			
	All - Printed	0.175 (0.03)	0.157 (0.05)	0.301			

Table 5: Analysis using k-cos function with various metrics for comparing cadaveric bone to printed models. Drilling procedure segments: (A) cortical mastoidectomy, (BCD) thinning procedures, (E) facial Recess.

		Drill Sensor			Thumb Sensor		
		Cadaveric (SD)	Printed	p	Cadaveric	Printed	p
Strokes/Second	A	1.602 (0.61)	1.452 (0.26)	0.404	1.486 (0.45)	2.355 (0.41)	0.017
	BCD	1.357 (0.52)	1.501 (0.46)	0.092	1.409 (0.44)	2.137 (0.63)	**0.0005**
	E	1.398 (0.43)	2.11 (0.28)	0.035	1.385 (0.08)	2.037 (0.30)	0.058
% Straight Strokes	A	0.637 (0.13)	0.316 (0.03)	**1.16E-11**	0.687 (0.12)	0.557 (0.15)	0.096
	BCD	0.688 (0.13)	0.328 (0.08)	**2.59E-14**	0.687 (0.13)	0.552 (0.17)	**0.003**
	E	0.71 (0.08)	0.416 (0.05)	**0.004**	0.813 (0.08)	0.576 (0.08)	**0.005**
% Curved Strokes	A	0.363 (0.13)	0.684 (0.03)	**1.16E-11**	0.311 (0.12)	0.443 (0.15)	0.092
	BCD	0.312 (0.13)	0.672 (0.09)	**2.59E-14**	0.313 (0.13)	0.448 (0.17)	**0.003**
	E	0.300 (0.09)	0.584 (0.05)	**0.004**	0.188 (0.08)	0.424 (0.08)	**0.005**
Short Strokes	A	0.394 (0.10)	0.229 (0.05)	**0.001**	0.696 (0.11)	0.685 (0.03)	0.632
	BCD	0.495 (0.22)	0.231 (0.12)	**6.33E-07**	0.635 (0.17)	0.660 (0.13)	0.534
	E	0.509 (0.12)	0.466 (0.19)	0.693	0.659 (0.03)	0.569 (0.18)	0.288
Medium Strokes	A	0.211 (0.08)	0.181 (0.03)	0.246	0.144 (0.06)	0.168 (0.03)	0.136
	BCD	0.173 (0.09)	0.167 (0.06)	0.763	0.156 (0.07)	0.172 (0.06)	0.389
	E	0.242 (0.08)	0.172 (0.05)	0.183	0.158 (0.06)	0.17 (0.05)	0.746
Long Strokes	A	0.394 (0.10)	0.59 (0.07)	**0.004**	0.160 (0.07)	0.147 (0.02)	0.457
	BCD	0.332 (0.18)	0.596 (0.17)	**2.12E-05**	0.209 (0.15)	0.168 (0.09)	0.195
	E	0.250 (0.08)	0.362 (0.18)	0.257	0.184 (0.07)	0.261 (0.15)	0.318
Time/Stroke	A	0.330 (0.11)	0.156 (0.02)	**2.76E-09**	0.447 (0.08)	0.317 (0.12)	0.044
	BCD	0.366 (0.10)	0.157 (0.05)	**6.18E-15**	0.431 (0.13)	0.311 (0.14)	**0.002**
	E	0.368 (0.11)	0.186 (0.03)	0.034	0.446 (0.03)	0.304 (0.14)	0.052