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A Novel 3D-Printed Training Platform for Ossiculoplasty with Objective Performance Evaluation

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Featured Application: This study highlights a novel application of 3D-printed models for training in ossiculoplasty with autologous incus remodeling. The use of both magnified (3:1) and real-sized (1:1) incus models enable trainees to build confidence and precision in complex surgical tasks. The inclusion of a quantitative scoring system based on CBCT imaging provides an objective, reproducible method to assess skill acquisition.

Abstract: Ossiculoplasty (OPL) aims to restore ossicular chain continuity to improve hearing in patients with conductive or mixed hearing loss, often performed during tympanoplasty. The current training methods, including cadaveric temporal bone models, face challenges such as limited availability, high costs, and biological risks, prompting the exploration of alternative models. This study introduces a novel training platform for OPL using 3D-printed temporal bones and incudes, including a magnified (3:1) model to enhance skill acquisition. Sixty medical students were divided into two groups: one trained on magnified models before transitioning to real-sized ones, and the other used only real-sized models. Training performance was quantitatively assessed using post-remodeling cone-beam CT imaging and mesh distance analysis. The results showed a significant improvement in performance for students with preliminary training on magnified models (87% acceptable results vs. 37%, p = 0.001). Qualitative feedback indicated higher confidence and skill ratings in the magnified model group. This study highlights the effectiveness of scalable, anatomically accurate synthetic models for complex surgical training. While further validation is required with experienced trainees and broader scenarios, the findings support the integration of 3D printing technologies into otologic education, offering a cost-effective, reproducible, and innovative approach to enhancing surgical preparedness.

Keywords: ossiculoplasty; 3D printing; surgical training; surgical simulation

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1. Introduction

Ossiculoplasty (OPL) is the surgical procedure aimed at restoring the continuity of the ossicular chain to improve hearing function in patients with conductive or mixed hearing loss. This surgery is commonly performed as part of tympanoplasty in cases of chronic otitis media (COM), trauma, or neoplasm [1–3], where the ossicular chain is eroded or fixed. Either autologous or heterologous materials can be used as prosthesis for OPL. While synthetic prostheses are pre-formed and do not usually require specific modeling before positioning into the middle ear, autologous materials (bone or cartilage) require proper graft remodeling to adapt to the residual ossicular chain and the tympanic membrane [4–8].

The delicate anatomy of the middle ear, combined with the small dimensions of grafts and prostheses, involves precise handling and expertise to safely and effectively manipulate these minute structures. Given the technical complexity of OPL, proper training is essential both for prosthesis positioning and, in autologous techniques, prosthesis sculpting [9,10]. Traditional training using cadaveric temporal bones provides the most realistic surgical experience of ear surgery. However, within cadaveric courses, time for OPL training is often constrained, as priority is typically given to comprehensive temporal bone dissection, rather than specific ossicular reconstruction skills. Additionally, the use of the cadaveric model poses challenges, such as limited availability, high costs and biological risks.

In recent years, new technologies such as 3D printing are becoming more popular as an alternative for training purposes. Particularly, 3D-printed models present the advantage of being able to standardize the training experience for all participants, providing a consistent platform for skill development. In addition to combining anatomical realism with reproducibility and scalability at relatively low costs, they provide the possibility to replicate complex anatomies and, most importantly, pathologies. These models have been already experienced for anatomical education [11], patient communication [12,13], preoperative planning [14,15] and surgical training [16–18]. Also, animal models [19–22], synthetic temporal bone models [23–25], and virtual reality simulators [26,27] were developed for training purposes across various fields of otorhinolaryngology, enabling residents to build confidence and skills before performing surgical procedures in a clinical setting. Most studies in the literature focus on temporal bone surgical simulators suited for microscopic dissection under both healthy and pathological conditions. Some authors have designed passive prostheses for ossicular chain reconstruction, prototyping them using 3D printing [28–32]. Other groups have focused on 3D-printed models for educational purposes [33], though few have specifically targeted ossiculoplasty. Existing temporal bone models are primarily aimed at mastoid dissection or endoscopic surgery, with limited emphasis to ossiculoplasty techniques [34–36].

The primary aim of this study was to develop a reliable training platform for ossiculoplasty with autologous remodeled incus, based on 3D printing. The feasibility of simulating incus remodeling and positioning of the reshaped ossicle into a pathological middle ear model was evaluated during dedicated training sessions involving medical students. Moreover, we tested the hypothesis that practicing the remodeling technique on a three-times magnified (3:1) incus model prior to using a real-sized incus could improve training performance.

2. Materials and Methods

2.1. Image Segmentation and Creation of Virtual Models

The virtual reconstruction of the temporal bone and middle ear was obtained from the thin-layer CBCT of a healthy volunteer. Image segmentation was performed using Mimics 26.0 Medical software (Materialise, Leuven, Belgium) to identify the main bony anatomical structures (ossicular chain, vestibule and semicircular canals, cochlea, facial nerve, carotid artery and sigmoid sinus).

The incus was the focus of the ossiculoplasty task in this experiment. A 3D model of the incus from the same CBCT was created and using 3-Matic software (v.19.1, Materialise, Leuven, Belgium), a rectangular geometry was subtracted from the surface of the incus model to create a reference notch for further analysis on the simulated incus remodeling. Subsequently, the obtained incus was magnified three times its original size to create an enlarged incus model (Figure 1).

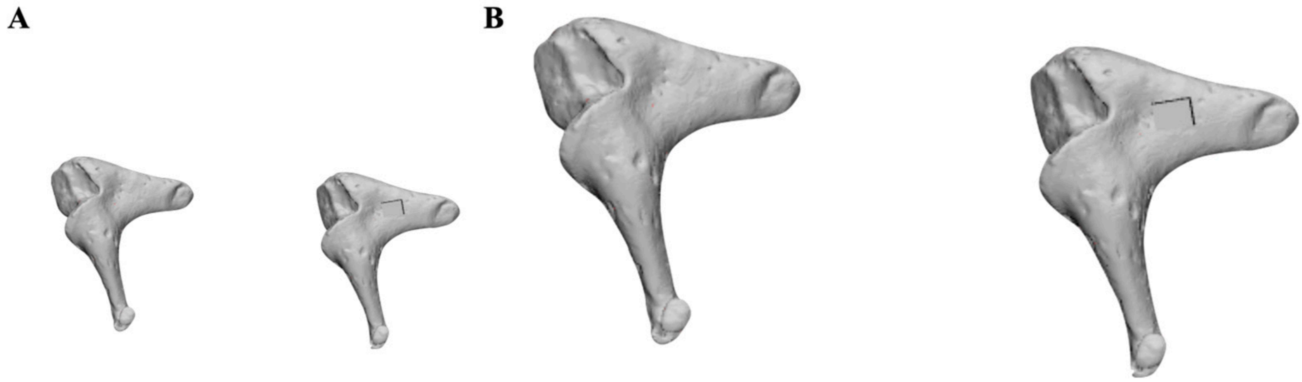

Figure 1. (**A**) Virtual model of the real-sized segmented incus (**left**) and the incus used for the ossiculoplasty task with the rectangular notch (**right**); (**B**) Virtual model of the 3-times magnified incus (**left**) and the incus used for the ossiculoplasty task with the rectangular notch (**right**).

Using 3-Matic software, a modified version of the temporal bone (mTB) was created to replicate the conditions for Partial Ossicular Replacement Prosthesis (PORP): the virtual incus was removed while the malleus and the stapes were left inside the tympanic cavity (Figure 2). The mTB could be used both for the insertion of the remodeled incus (autologous PORP) after the ossiculoplasty task or synthetic prostheses (synthetic PORP).

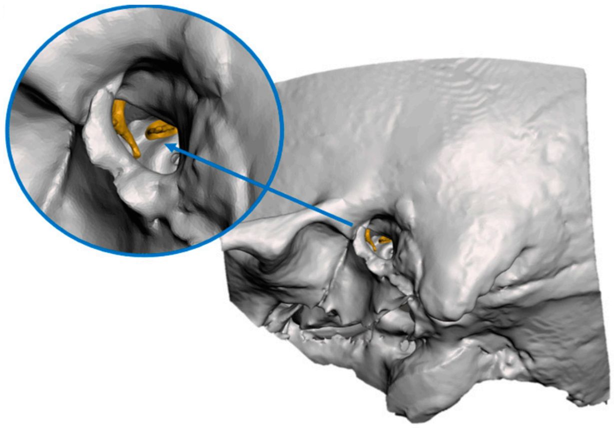

Figure 2. Temporal bone model without incus.

2.2. 3D Printing of the Models

From the virtual models of the real-sized and magnified incudes, sixty 1:1 and thirty 3:1 incudes were 3D printed with stereolithography (SLA) technology, through the Formlabs Form 3B 3D printer (Formlabs, Somerville, MA, USA) using standard White V4 resin, with a layer thickness of 0.050 mm. The mTB was printed with the same printer (Figure 3).

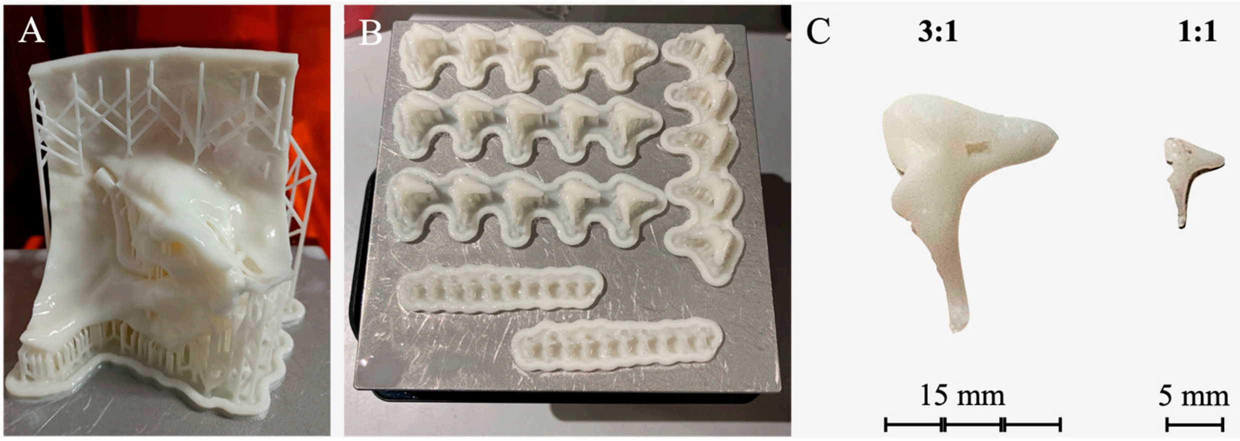

Figure 3. (**A**,**B**) Temporal bone model and incudes after printing. (**C**) Real-sized (1:1) and magnified (3:1) incudes ready for use.

After printing, all the models were soaked in denatured alcohol for 5 min, the supports removed, and the models left to dry. Then, following the manufacturer's instructions, the models were cured for 30 min at 60 degrees to complete the polymerization process.

2.3. Ossiculoplasty Simulation Hands-On Session

Sixty final-year medical students from the Faculty of Medicine and Surgery of the University of Bologna experienced the novel training method based of 3D-printed models between April 2024 and July 2024. The training sessions started with a standardized introductory lecture delivered by two of the authors (C.L., A.B.), providing a general overview of incus remodeling for OPL and explaining the steps to be followed during the practical exercises. All the students replicated the same type of incus remodeling (drilling of the long process, partial drilling of the short process, smoothing of the superior edge, and creation of the hole for the stapes head at the base of the long process) with an operative microscope. The lecture was followed by the practical session, preceded by the demonstration of ossicle drilling by one of the authors (C.L., A.B.).

The participants were homogeneously divided into two groups (A and B), each consisting of thirty students.

Participants from Group A performed a preliminary ossiculoplasty task on the magnified incus (3:1), before replicating it on the real-sized incus (1:1). Participants from Group B performed the ossiculoplasty task only once, directly on real-sized incus (1:1).

After the completion of the tasks, all the participants had the possibility to insert the remodeled real-sized incudes into the mTB using both a microscope and an endoscope. All trainees managed to complete the whole training experience. Training sessions for group A consisted of 5 4-h sessions, during which every student performed the ossiculoplasty first on the 3:1 incus and immediately afterwards on the 1:1 incus. On the contrary, the training session for group B on the 1:1 model was completed in 3 sessions, each 4 h long.

At the end of the training session, participants were asked to complete a qualitative questionnaire. The survey was divided into three main sections: The first two regarded the use of the instruments on the 3D-printed incudes (both real-sized and magnified). The third section was general and regarded the interest in using 3D-printed models for specific training purposes.

The task on the real-sized incus was also completed by an experienced surgeon (G.M.), who remodeled five real-sized incudes and whose performance was taken as a reference for the subsequent evaluation of the two groups.

All the real-sized incudes obtained (from the participants and the experienced surgeon) were scanned via CBCT according to three configurations (A, B, C), each corresponding to a different positioning of the parts during the scanning process. The obtained images were segmented using the same thresholding parameters (−240 ± +360 HU) with Mimics.

2.4. Error Range Quantification

To quantitatively assess the performance of participants from both groups, a preliminary evaluation to estimate a reasonable error range was conducted (Figure 4). Two types of error were specifically evaluated: the first pertains to the error introduced by the CBCT scan and image segmentation ("segmentation error"), while the second relates to performance variability when the same operator repeats the incus remodeling task multiple times ("intra-operator error").

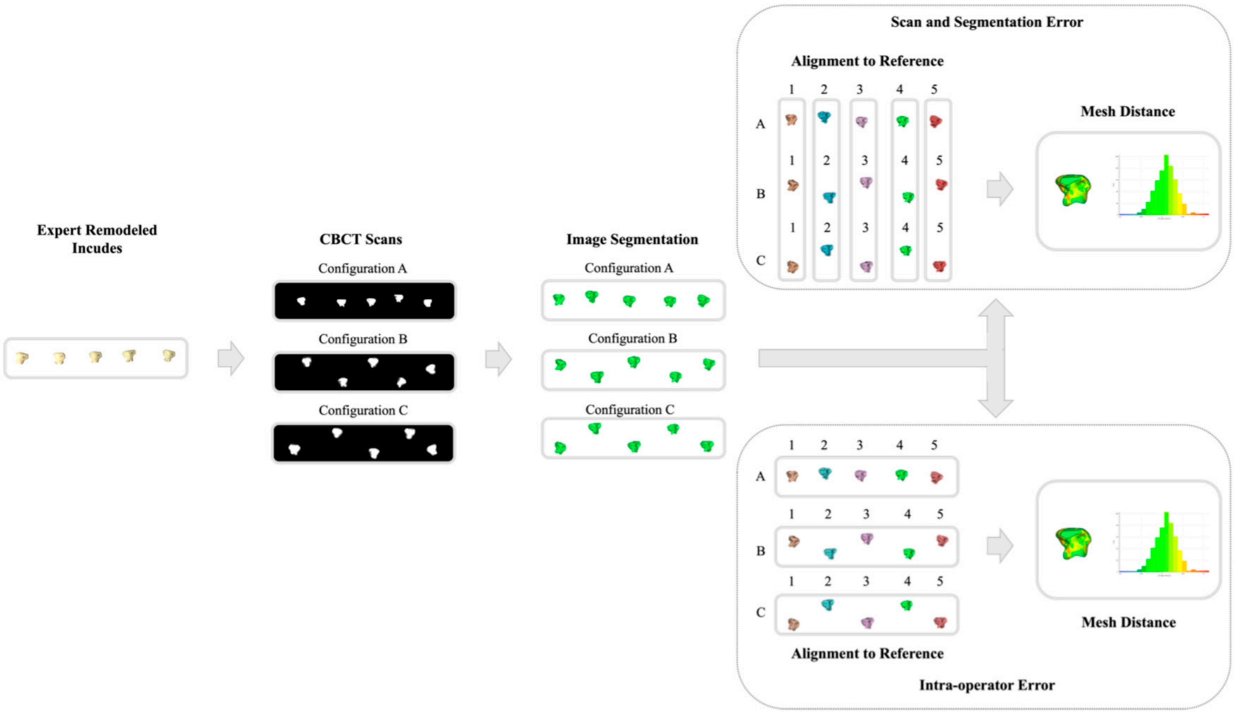

Figure 4. Workflow for the assessment of error range: segmentation error (**top right**) and intra-operator error (**bottom right**). A, B, C: scan configurations. 1, 2, 3, 4, 5: incus remodeling task repetition indicator.

To assess this, the configurations from the five 3D incus models obtained by the experienced surgeon were imported in Cloud Compare software (v2.12.3), and for the segmentation error, the mesh distance between the same incus models in different positions were compared. The alignment between the two meshes was performed using the four vertices of the reference rectangular notch provided in the printed ossicle. Particularly, as reported in Figure 4 (top right), the same remodeled ossicle was compared along the three A, B, C configurations (see the column groupings shown in Figure 4 top right). For each comparison, the A configuration was taken as a reference, and the other two scans (B, C) were aligned to A. The software returns a colorimetric map that reflects the distance of each point of the analyzed mesh from its corresponding point on the reference mesh.

Similarly, for the intra-operator error, the mesh distance between the incus bones from the same scan (see the row groupings shown in Figure 4, bottom right) was computed. Particularly, A2, A3, A4, and A5 were aligned to A1, taken as a reference, then B2, B3, B4, and B5 were aligned to B1, and C2, C3, C4, and C5 were aligned to C1.

2.5. Quantitative Performance Analysis

After determining the error range, the performance of the two groups was evaluated. The workflow of the quantitative evaluation of the two groups' performance is reported in Figure 5. The files obtained by the sixty real-sized remodeled incudes were imported into Cloud Compare software, and each incus was aligned to the reference incus remodeled by the experienced surgeon. Once the alignment was done, the software calculated the distance between the meshes remodeled by study participants and the reference one. We decided to use the first incus reshaped by the expert surgeon as the reference incus, to avoid any bias caused by task repetition. After all these alignments, the data were recorded in Microsoft Excel and statistical analysis (Pearson Chi-Square test, $\alpha = 0.05$) was performed using Stata 18.0 software (StataCorp LLC, College Station, TX, USA).

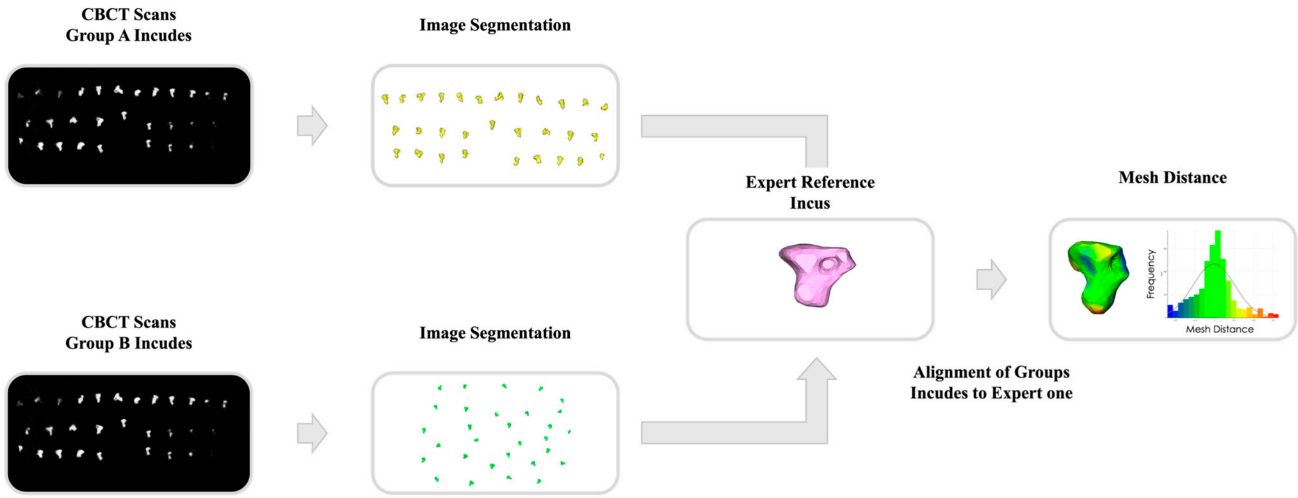

Figure 5. Workflow of the quantitative assessment of the groups' performance.

3. Results

3.1. Error Range

The average segmentation error for the incudes remains entirely within the ±0.35 mm range, which corresponds to 10% of the maximum dimension of the remodeled incus. This range was therefore chosen as the starting point for evaluating the performance of the study participants.

For the intra-operator error, the analysis of the mesh distance among the five-time repeated remodeling within the same scan confirmed that most of the distance points remained within the ±0.35 mm range found for the segmentation error. Specifically, a small average percentage of points (1 ± 1%, i.e., ranging between 0 and 2%) fell outside this range.

Starting from this percentage (2%) of "outside-range" points related to the experienced surgeon, we decided to grant an additional margin, therefore considering acceptable the remodeled incudes with a percentage of points outside the segmentation error range not exceeding the 3%.

3.2. Quantitative Performance Results

Considering the above-mentioned error ranges and tolerances, the number of acceptable remodeled incudes was 26 out of 30 (87%) for Group A and 11 out of 30 (37%) for Group B. Statistical analysis exhibited a significant difference between the performance of the two groups with a p-value of 0.001 (Figure 6).

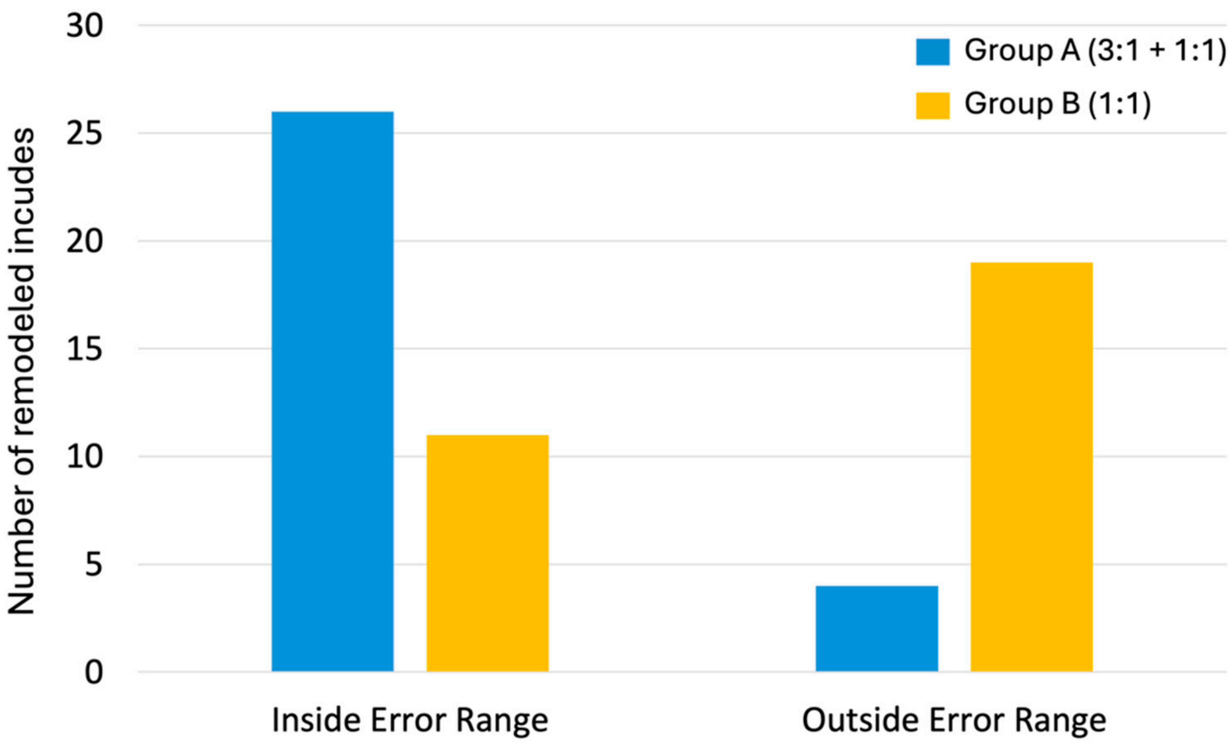

Figure 6. Graphic representation of the quantitative results of the performance evaluation for the two groups.

3.3. Qualitative Questionnaires

The questions posed to all the participants and the obtained results are reported in Figure 7A. Generally, the scores obtained from Group A were higher than those of Group B regarding the feeling of instruments on real-sized 3D-printed incus, suggesting a more confident approach to the real-sized incus after performing the task on the magnified incus. Particularly, the feeling of instruments while performing ossiculoplasty on the real-sized incus was rated higher in Group A than in Group B. Specifically, for the use of the operative microscope, the mean score in Group A was 3.5, compared to 2.6 in Group B. The use of Klemmer forceps to hold the model was rated 2.9 in Group A and 2.4 in Group B. The identification of the drilling sites on the model was rated 2.7 in Group A and 2.2 in Group B. The use of the drill was rated identically for both groups.

Moreover, participants in Group A rated the use of instruments on the magnified incus slightly better than real-sized incus during ossiculoplasty for all the instruments.

Regarding general aspects of the training process, both groups provided high ratings. All the participants agreed with the usefulness of 3D-printed simulators in surgical training and education, with a mean score of 4.7 in Group A and 4.5 in Group B. Similarly, the recommendation of 3D-printed models to other medical students received a score of 4.7 in Group A and 4.8 in Group B. Additionally, participants in Group B expressed a preference for training on a larger model before transitioning to the real-sized incus, rating on average this statement 4.8 out of 5.

A

QUESTIONS (5-point Likert Scale)

Use of the instruments
Q1: Use of the operative microscope
Q2: Use of the Klemmer forceps
Q3: Use of the drill
Q4: Identification of drilling sites

General questions
Q5: The 3:1 incus was easy to work with during the ossiculoplasty procedures
Q6: The real-size incus was easy to work with during the ossiculoplasty procedures
Q7: Practicing bone remodeling on the 3:1 incus was useful to understand ossiculoplasty sculpting
Q8: Practicing bone remodeling on the enlarged (3:1) incus helped me to perform the procedure more effectively on the real-size (1:1) model
Q9: I feel that practicing bone remodeling on the enlarged (3:1) model was necessary before simulating it on real-sized incus
Q10: I consider 3D printed simulators useful in my surgical training and education
Q11: I would recommend surgical training with 3D printed models to other medical students
Q12: The current 3D printed models and training process could be improved for better learning outcomes
Q13: I would have preferred to perform bone remodeling on a larger model before simulating it on real-size (1:1) incus

B

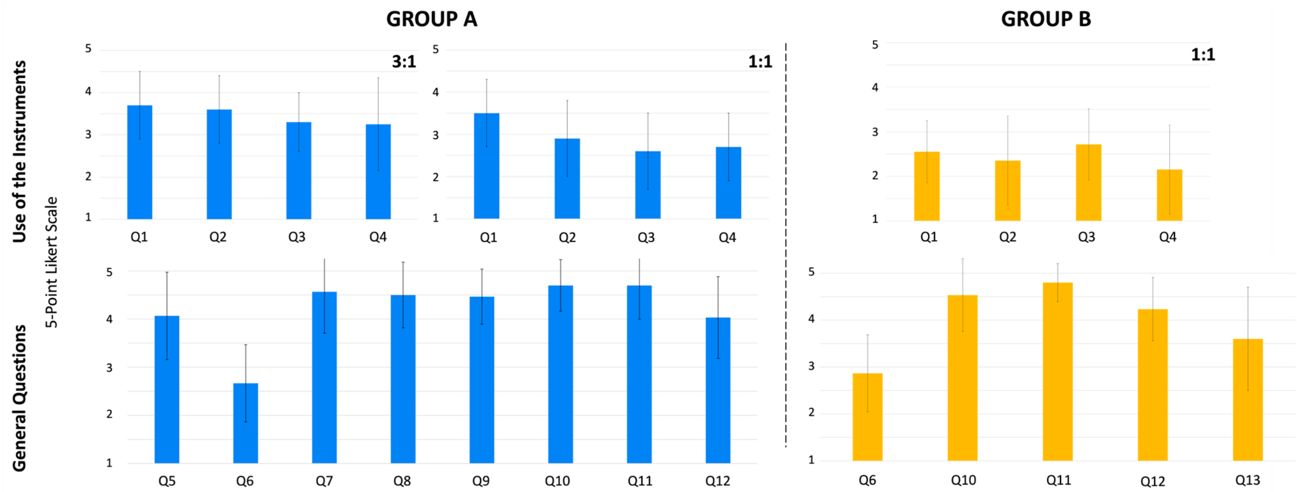

Figure 7. (**A**) Questions of the qualitative questionnaire posed to all participants. (**B**) Results of the qualitative questionnaires obtained for Group A (**left**) and results obtained from Group B (**right**).

4. Discussion

In this study, we tested the suitability of 3D-printed incudes for practicing autologous ossiculoplasty. Ossiculoplasty (OPL) continues to be a surgical technique that is often sidelined during training programs of young surgeons. Like previous studies in otology, our research supports the idea that 3D printing technology may provide a cost-effective and easily repeatable training solution, with a high level of fidelity in reproducing the surgical conditions. Specifically, we focused on the potential beneficial effect of performing ossiculoplasty first on magnified 3D-printed incudes, before transitioning to real-sized incudes. To the authors' knowledge, this hypothesis has not been previously investigated, and no group has proposed a standardized scoring system to objectively assess the trainee performance in this surgical technique.

Particularly, the existing literature remains sparse regarding studies focusing exclusively on OPL. Rose et al. [34], developed a 3D-printed multimaterial and multicolor temporal bone model with significant anatomical detail and closely resembling human cadaver specimens for drilling and dissection. The model was intended for total temporal bone dissection and it was also possible to insert a cochlear implant. Stramiello et al. [36], anatomically validated a 3D-printed pediatric middle ear model for endoscopic ear surgery, despite participants were not involved in dissecting the model. Mukherjee et al. [31], focused on the resolution of the imaging to produce accurate 3D-printed ossicle models and proposed a new design of customized middle ears, to have better long-term results in ossiculoplasty. However, the study did not focus on practical ossiculoplasty tasks. Brumpt et al. [33], demonstrated the efficacy of 3D-printed anatomical models of the ear to study anatomy compared to cadaver, while Kuru et al. [35], developed an artificial middle ear model combining 3D printing and silicone rubber molding with a reproducible acoustic behavior. Sokolowski et al. [29], Heikkinen et al. [32], and Kamrava et al. [30], investigated different 3D printing materials and designs to realize innovative middle ear prostheses. The studies were conducted on cadavers, starting from CBCT and micro-CT imaging, respectively. Both groups demonstrated the feasibility of designing a customized prosthesis from patient imaging, but both agreed about the need for more data to investigate the acoustic properties and real biocompatibility of 3D-printed materials. Regarding the need for specific training for OPL, Lähde et al. [28] was the only study that focused on practical OPL, integrating 3D-printed temporal bone models and middle ear prosthesis in otosurgical training. The participants had a rigid 3D-printed temporal bone model: They had to establish anatomical landmarks of the middle ear and then perform OPL. After the completion of OPL task, they had to insert a 3D-printed PORP and at the end of the simulation the participants had to complete a qualitative questionnaire. Despite the focus being more on practice for ossiculoplasty, the feedback was qualitative rather than quantitative.

Our findings demonstrate that initial practice on a magnified 3D-printed incus significantly enhanced the trainee's experience in OPL. Group A, which began training on the magnified model before transitioning to the real-sized incus, achieved an impressive 87% of acceptable results. Indeed, the performance of Group A on real-sized incus could have also been influenced by the task repetition. However, when passing from the scaled incus to the real-sized one, the task cannot be considered the same, since it involves substantial operational differences, such as microscope focusing, the grip and handling on the ossicle and the size of the drill. Therefore, the observed performance improvement can primarily be attributed to the effect of practicing with the scaled model, which enhances understanding of the anatomy and increases awareness of the drilling process.

In this study, a novel scoring system based on CBCT post-remodeling imaging allowed an objective, structured approach to assess and compare trainee progress, moving beyond subjective assessments, which has long been the only type of evaluation for trainees in several surgical fields. However, it is important to note that this quantitative score is designed purely for educational purposes within a training setting and is not intended for direct application in clinical scenarios. The controlled nature of this scoring ensures that it serves as a tool for enhancing training effectiveness rather than as a predictor of clinical outcomes.

Interesting insights were also observed from the responses to the qualitative questionnaire. Specifically, regarding the use of instruments on the real-sized incus, participants in Group A gave higher scores compared to those in Group B, except for the use of the drill. This may strengthen the hypothesis that using a magnified incus before performing the task on a real-sized incus can indeed have a beneficial effect by increasing awareness in task execution. Regarding the general questions part, the majority of the participants agreed or strongly agreed about the usefulness and realism of these models for their training, and participant of Group A agreed on the effectiveness of using a magnified incus before transitioning to a real-sized incus. However, they still reported difficulty performing the ossiculoplasty task on the real-sized incus. In general, most of the participants were enthusiast about the training experience and would recommend this experience to other medical students.

Limitations and Future Outlook of the Study

This study has some limitations. All the participants were medical students without prior surgical experience, which may have influenced the outcomes. It is possible that more experienced individuals might show less improvement with the magnified model, potentially failing to demonstrate the same statistical significance. Furthermore, we did not assess the long-term impact of the training intervention. While a significant difference was observed within a single session, the absence of a learning curve analysis limits our ability to determine whether the training advantages translate into sustained skill improvement over time. A factor to consider is the potential effect of task repetition, as participants in Group A performed the ossiculoplasty twice (first on a 3:1 incus and then on a 1:1 incus), while participants in Group B performed the ossiculoplasty only once on a 1:1 incus. This difference raises the possibility that the improved performance in Group A may be partially attributed to repeated exposure rather than solely to the benefits of magnification. However, when passing from the scaled incus to the real-sized one, the task cannot be considered strictly the same, since it involves substantial operational differences, such as microscope focusing, the grip and handling on the ossicle and the size of the drill. The observed performance improvement is likely mainly due to practicing with the scaled model, which improves understanding of the anatomy and increases awareness of the drilling process, rather than the task repetition itself.

Moreover, qualitative feedback from the participants strongly highlighted the advantages of using a magnified incus prior to operating under real-size conditions. The subjective assessments consistently indicated that the stepwise approach facilitated better spatial orientation, improved instrument handling, and increased confidence when transitioning to the standard-sized model. These findings suggest that integrating magnified training models into surgical education may enhance skill acquisition, but further studies incorporating longitudinal assessments are necessary to confirm the benefits of this approach. The comparison between learning curves obtained from different training workflows, combining repetitive modelling on 3:1 and 1:1 ossicles, will allow the definition of the most effective training workflow for incus remodeling.

Eventually, future research should focus on refining the anatomical fidelity of the 3D-printed models and exploring alternative materials to enhance both tactile feedback and visual precision. Expanding the scope of 3D-printed models to encompass diverse anatomies and pathologies could be highly beneficial in developing comprehensive training frameworks for otologic surgery, ensuring that surgeons are equipped to handle a broad spectrum of clinical scenarios.

5. Conclusions

The use of a magnified 3D-printed incus, in combination with the repetition of the task in surgical training represents an effective adjunct to traditional training approaches, offering promising enhancements in skill acquisition for complex procedures, such as OPL. Introducing quantitative scoring in this context provides a novel metric for evaluating training progress. This study supports the integration of scalable, anatomically accurate synthetic models into surgical education, as a step forward in advancing clinical practice readiness.

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(Gabriele Molteni) and R.D.; supervision, G.M. (Giulia Molinari), L.A., L.C., I.J.F., L.P., G.M. (Gabriele Molteni) and E.M. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: The subject provided written informed consent to take part in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

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