Received: 16 June 2026; Revised: 05 Aug. 2026; Accepted: 03 Sep. 2026
https://doi.org/10.22306/atec.v12i3.357

Development of silicone anatomical facial models intended for surgical suturing training

Branko Štefanovič
Technical University of Košice, Faculty of Mechanical Engineering Department of Biomedical Engineering and Measurement, Letná 1/9, Košice 040 01, Slovak Republic, EU, branko.stefanovic@tuke.sk (corresponding author)
Natália Antolová
Technical University of Košice, Faculty of Mechanical Engineering Department of Biomedical Engineering and Measurement, Letná 1/9, Košice 040 01, Slovak Republic, EU, natalia.antolova@student.tuke.sk
Bibiána Ondrejová
Technical University of Košice, Faculty of Mechanical Engineering Department of Biomedical Engineering and Measurement, Letná 1/9, Košice 040 01, Slovak Republic, EU, bibiana.ondrejova@tuke.sk
Jozef Živčák
Technical University of Košice, Faculty of Mechanical Engineering Department of Biomedical Engineering and Measurement, Letná 1/9, Košice 040 01, Slovak Republic, EU, jozef.zivcak@tuke.sk

Keywords: anatomical training model, surgical suturing, silicone casting, 3D printing, medical simulation.
Abstract: Simulation-based training plays an important role in surgical education by providing a safe environment for developing practical skills. However, commercially available suturing simulators are often expensive and offer limited possibilities for anatomical customization. The aim of this study was to develop a low-cost anatomical eyebrow model for surgical suturing training using three-dimensional (3D) scanning, additive manufacturing, and silicone casting technologies. A 3D scan of the facial region was acquired and processed to create a digital model of the eyebrow area. A simulated laceration was incorporated into the model using computer-aided design (CAD) tools. A two-part mould was designed and manufactured using fused deposition modelling (FDM) 3D printing. The final training model was produced by casting a two-component silicone elastomer into the printed mould. Manufacturing feasibility, production costs, and functional usability were evaluated. The proposed workflow successfully enabled the fabrication of an anatomically shaped silicone eyebrow model suitable for practising basic suturing techniques, including needle handling, wound-edge approximation, and knot tying. The prototype accurately reproduced the intended anatomical geometry and wound morphology. The total material cost of the first prototype, including mould fabrication and silicone casting, was approximately €4.89, while subsequent models can be produced at substantially lower cost due to mould reusability. Functional testing confirmed the suitability of the model for basic surgical skills training. The results demonstrate that the combination of 3D scanning, CAD modelling, additive manufacturing, and silicone casting provides a feasible and cost-effective approach for developing customized anatomical training models for surgical education.

1 Introduction

Simulation-based medical education has become an integral component of modern surgical training, providing a safe and controlled environment for the development of technical skills before their application in clinical practice [1-4]. In surgical education, simulation enables repetitive practice of suturing techniques, needle handling, knot tying, and tissue manipulation without exposing patients to unnecessary risk. Numerous studies have demonstrated that simulation-based training improves technical proficiency, confidence, and overall clinical performance while contributing to patient safety [1,2,4].

A wide range of training models has been developed for surgical suturing education. These models can be broadly categorized as biological, improvised, commercial synthetic, and additive-manufactured models. Biological models, including animal tissues and cadaveric specimens, provide the highest degree of anatomical and tactile realism due to their natural tissue architecture and mechanical properties [5-9]. However, their routine use is limited by ethical concerns, hygiene requirements, storage conditions, restricted availability, and higher operational costs [7,9].

Improvised training models, such as fruit, foam, or textile-based substitutes, represent a low-cost alternative for acquiring basic suturing skills. Although suitable for developing fundamental hand–eye coordination and instrument handling, these models fail to reproduce the layered structure and biomechanical behaviour of human tissue, limiting their value for advanced surgical training [5,6,10]. Synthetic commercial simulators offer improved standardization and repeatability, but their cost often restricts widespread adoption, particularly when anatomically detailed or multilayered models are required [6,11].

CC BY NC

Recent advances in additive manufacturing have created new opportunities for the development of customized surgical training models. Additive manufacturing enables the fabrication of anatomically accurate structures with high reproducibility and relatively low production costs [12-15]. In particular, the combination of 3D-printed moulds and silicone casting has emerged as a promising approach for producing realistic soft-tissue simulators. Silicone-based materials are widely used because of their biocompatibility, durability, and ability to mimic the viscoelastic properties of human skin [16,17]. Furthermore, additive manufacturing allows the production of patient-specific or anatomically targeted models, thereby enhancing the educational relevance of simulation-based training [12,14].

Despite significant progress in surgical simulation, no currently available model simultaneously provides high anatomical fidelity, realistic mechanical behaviour, affordability, durability, and ease of customization. Consequently, there remains a need for training models that effectively combine these characteristics while remaining accessible for routine educational use. Therefore, the present study focuses on the design and fabrication of silicone anatomical facial models for surgical suturing training using a combination of CAD (Computer Aided Design) modelling, additive manufacturing, and silicone casting technologies. The proposed approach aims to provide a cost-effective and anatomically realistic training platform suitable for the development of practical suturing skills in facial surgery.

2 Methodology

The design process began with the definition of functional and ergonomic requirements for a silicone anatomical trainer intended for practising suturing techniques in selected facial regions. The model was required to provide realistic handling during needle penetration, suture tightening, knot tying, and wound-edge approximation. Attention was given to material elasticity, tensile behaviour, resistance to tearing, haptic feedback, and compatibility with standard surgical instruments. These requirements were based on previously reported mechanical characteristics of artificial skin and soft-tissue simulators, especially Young's modulus, tensile strength, viscoelastic behaviour, and puncture-related response [16,18].

From an ergonomic perspective, the model had to be compact, stable during manipulation, easy to handle, and suitable for repeated training. The geometry was designed to reproduce clinically relevant facial regions while preserving sufficient space for the manipulation of forceps, needle holders, and sutures. Stability during training was considered essential, as uncontrolled movement of the model can negatively affect the realism and repeatability of the exercise [15,19].

The eyebrow region was selected for the development of the anatomical suturing model due to its suitability for basic surgical skills training. This anatomical area provides sufficient geometric complexity to simulate realistic clinical conditions while remaining appropriate for practising fundamental techniques such as needle handling, wound-edge approximation, knot tying, and suture placement. Furthermore, the eyebrow region is a common site of facial lacerations encountered in clinical practice, making it relevant for educational applications. Consequently, all subsequent stages of digital modelling, mould design, fabrication, and functional evaluation were focused exclusively on the development of an anatomical eyebrow model.

2.1 Digital modelling of a simulated defect

A 3D scan of a human head was used as the basis for the development of the anatomical eyebrow model. The scan was acquired under stable indoor lighting conditions using a handheld structured-light 3D scanner Artec Eva (Artec 3D, Luxembourg, Luxembourg), with the scanning frequency of 16 fps (framer per second). The raw scan data were processed to remove environmental artefacts and irrelevant geometry in Artec Studio 13 (Artec 3D, Luxembourg, Luxembourg) software. The cleaned polygonal mesh was exported in STL format and used for subsequent computer-aided design processing.

The STL model was imported into Autodesk Meshmixer (Autodesk, Inc., San Francisco, CA, USA) CAD software, where the eyebrow region was isolated from the complete facial scan (Figure 1 – a). Mesh complexity was reduced to improve computational efficiency while preserving clinically relevant anatomical features. Surface irregularities resulting from the scanning process were corrected using smoothing and sculpting tools to obtain a clean and anatomically representative model suitable for further modification. The simulated laceration was subsequently incorporated into the eyebrow model. The defect was created using an auxiliary geometric body that was subtracted from the anatomical surface through a Boolean operation. The resulting wound geometry was further refined using sculpting tools to generate realistic wound edges and tissue contours. The final defect (Figure 1 – b) was designed to facilitate the practice of fundamental suturing techniques, including interrupted sutures, wound-edge approximation, and knot tying. The position, dimensions, and geometry of the simulated wound can be modified according to specific training requirements, enabling the creation of customized training scenarios.

CC BY NC

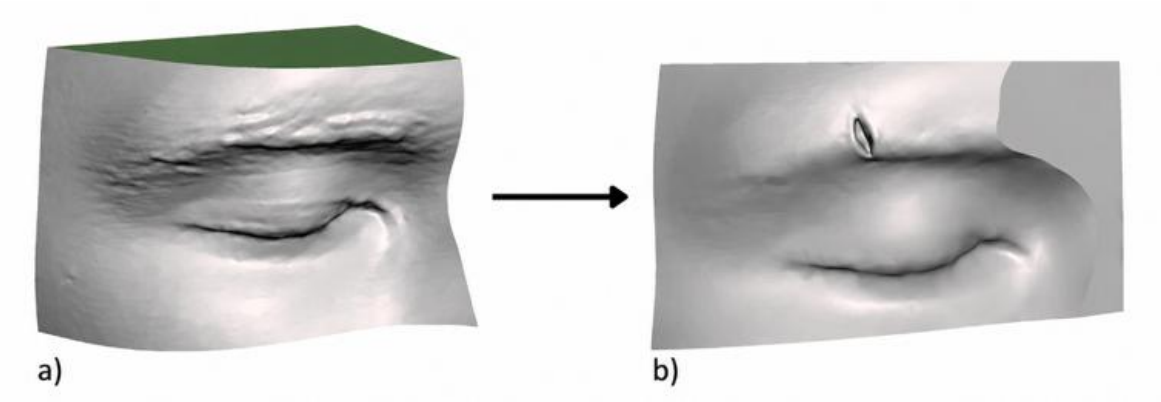


Figure 1 Digital model of the eyebrow before (a) and after (b) defect creation

2.2 Design of moulds for silicone casting

The mould for the anatomical eyebrow model (Figure 2) was designed in Autodesk Meshmixer. The mould geometry was created by generating a negative cavity through the subtraction of the anatomical model from a solid block. A two-part mould configuration was selected to allow straightforward fabrication, assembly, and demoulding of the final silicone cast. The mould incorporated alignment pins and corresponding sockets to ensure accurate positioning of both mould halves during assembly. In addition, a main inlet channel and multiple ventilation channels were integrated into the design to facilitate controlled silicone injection and efficient air evacuation during the casting process. The position of the parting plane was carefully selected to minimize undercuts, simplify demoulding, and reduce the risk of damaging the silicone model during removal from the mould. These design features were incorporated to improve manufacturing reproducibility and ensure consistent production of anatomically accurate silicone training models.

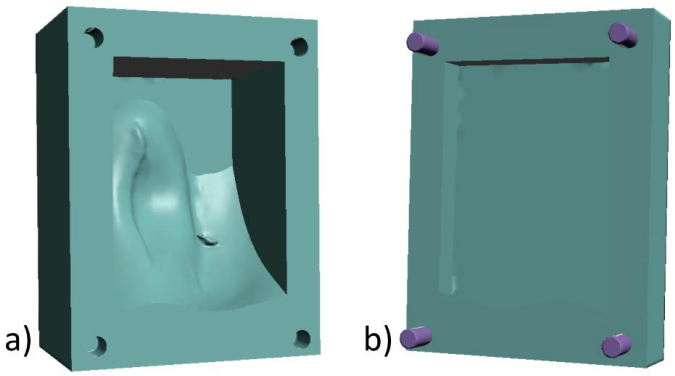


Figure 2 Digital mould design for the anatomical eyebrow model (a – negative cavity, b – mould cover with alignment pins)

2.3 Additive manufacturing of moulds

The mould was manufactured using the iFactory One Pro (iFactory3D GmbH, Dusseldorf, Germany) FDM (Fused Deposition Modelling) printer. The digital mould file was prepared in slicing software ideaMaker (iFactory3D GmbH, Dusseldorf, Germany) with a layer height of 0.2 mm, providing a suitable balance between surface quality and manufacturing time (Figure 3). The mould was printed from polyethylene terephthalate glycol (PETG), a material selected for its toughness, dimensional stability, and resistance to mechanical loading during mould assembly and silicone casting. To reduce material consumption while maintaining sufficient structural rigidity, a low infill density was applied. The mould was oriented on the build platform to avoid the use of support structures, thereby simplifying post-processing and reducing printing time. Following slicing, the generated G-code was transferred to the FDM printer for fabrication of the mould components.

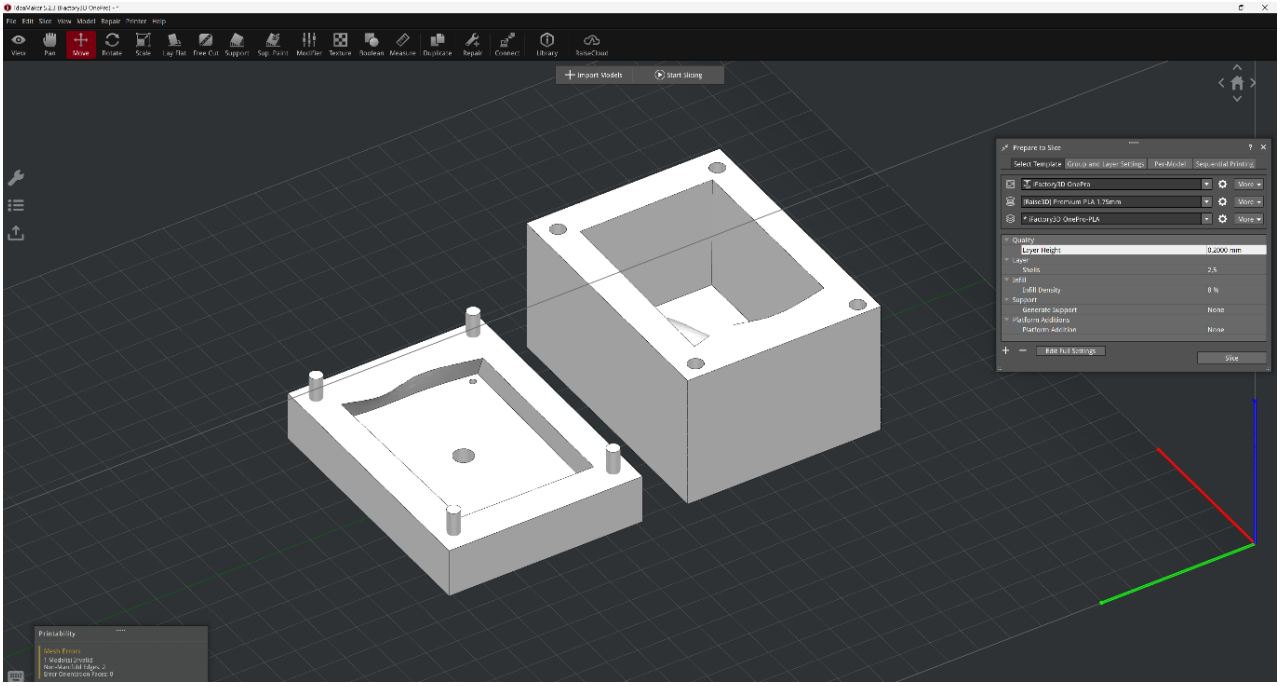


Figure 3 Preparation of the mould for 3D printing

2.4 Silicone casting and post-processing

A two-component casting silicone (EPOXY s.r.o, Vysoká pri Morave, Slovakia) was used for the fabrication of the anatomical eyebrow model. Prior to casting, the internal surfaces of the mould were coated with a thin layer of release agent to facilitate demoulding and prevent adhesion between the silicone and the mould walls. The mould components were subsequently assembled and mechanically secured using clamps to ensure accurate alignment and maintain sufficient pressure during casting. The silicone components were weighed according to the manufacturer's recommended mixing ratio of 1:1 and thoroughly mixed until a homogeneous mixture was obtained. The silicone was then injected into the mould through the inlet channel using a syringe (Figure 4 – a). Injection continued until material emerged from the ventilation channels, indicating complete filling of the mould cavity and displacement of trapped air (Figure 4 – b). The mould remained closed throughout the curing process to maintain dimensional accuracy and prevent deformation of the final model (Figure 4 – c). After complete curing, the mould was disassembled and the silicone eyebrow model was carefully removed. Residual material originating from the inlet channel, ventilation channels, and parting line was removed by mechanical trimming. Finally, the model was cleaned to eliminate any remaining release-agent residues, and a thin layer of fine talc was applied to the surface to reduce tackiness and provide a more realistic matte texture resembling human skin.

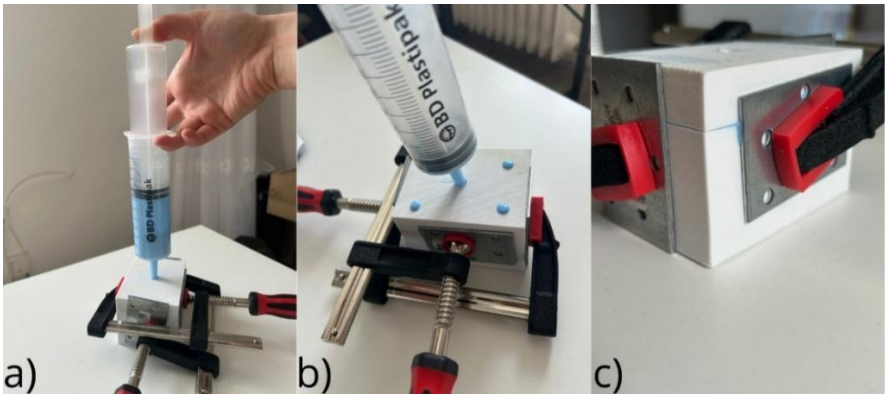


Figure 4 Silicone casting process, including mould fixation, injection, and demoulding

After curing, the mould was disassembled and the silicone model was removed. Excess material from the inlet, ventilation channels, and parting line was mechanically trimmed. The model was cleaned to remove separation residues, and the surface was treated with fine talc to reduce tackiness and create a more skin-like matte appearance.

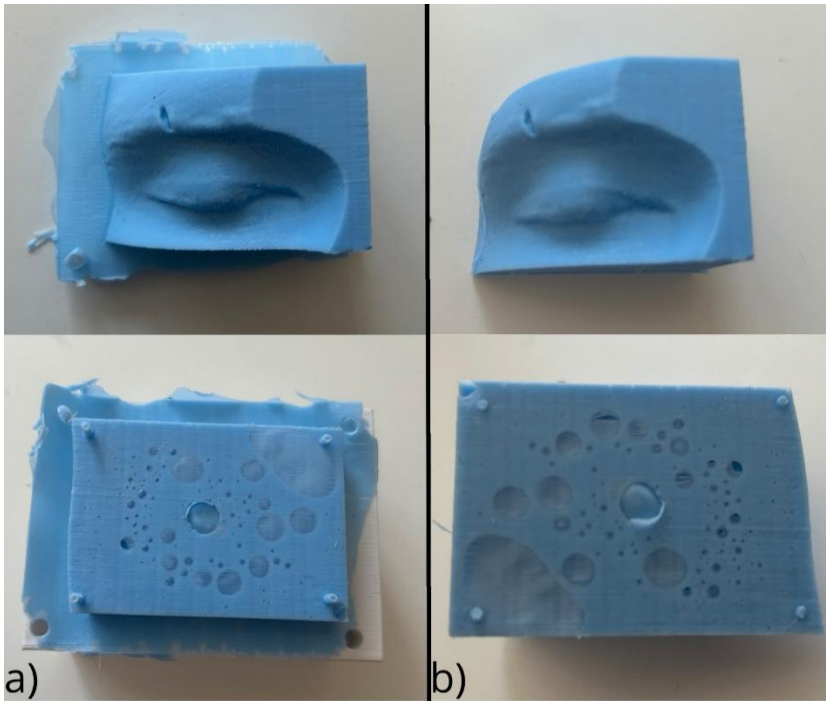


Figure 5 Silicone anatomical model before (a) and after (b) postprocessing

2.5 Functional testing

The eyebrow prototype was evaluated by practical suturing using standard surgical instruments (Figure 6). Testing was performed by a fourth-year medical student familiar with basic surgical techniques. The evaluation focused on haptic response, resistance to needle penetration, wound-edge approximation, material behaviour during knot tying, stability of the model, and overall usability. A structured evaluation form was used. Quantitative parameters were rated on a five-point scale, where 1 represented an unsatisfactory result and 5 represented an excellent result. Qualitative feedback was also collected to identify specific strengths and limitations of the prototype.

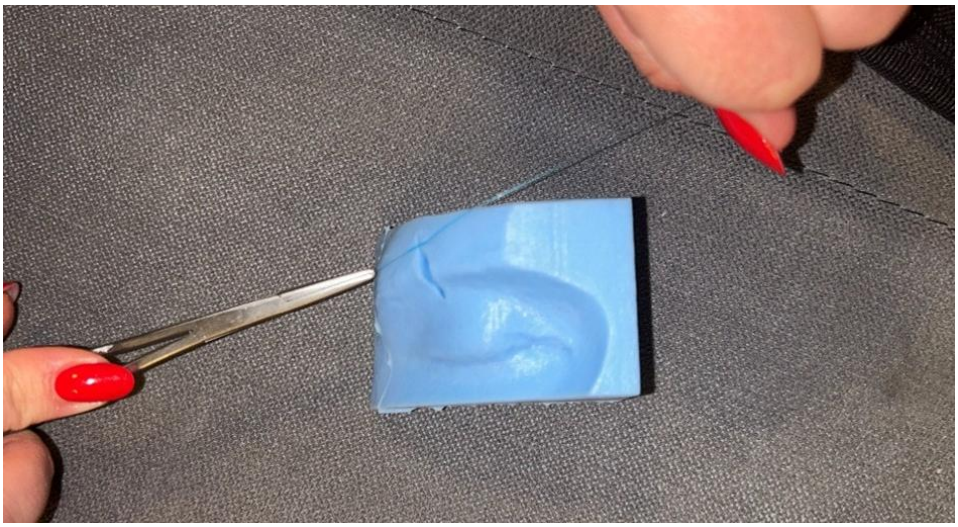


Figure 6 Functional suturing test performed on the eyebrow prototype

2.6 Economic and environmental assessment

The economic assessment included material consumption for the printed moulds and silicone casts. The moulds were considered reusable; therefore, the main variable cost for repeated production was the silicone volume required for each cast. The environmental assessment focused on material waste, reusability of moulds, elimination of biological waste, and the limitations associated with non-biodegradable silicone materials.

3 Results

3.1 Functional suturing test

Functional testing (Figure 7) demonstrated that the prototype could be used for basic suturing practice. The model remained stable during manipulation and allowed the use of standard surgical instruments. The anatomical shape and wound depth were positively evaluated, particularly in comparison with flat suturing pads.

However, the material properties of the initial silicone were rated as unsatisfactory in all quantitative categories. Haptic response, needle penetration resistance, wound-edge approximation, and resistance to tearing during knot tying were all rated 1 out of 5. The main limitation was the excessive stiffness of the silicone material, which did not adequately reproduce the behaviour of human soft tissue. Similar limitations have been reported in synthetic simulators when the mechanical properties of the material do not correspond sufficiently to biological tissue.

Despite this limitation, the tester considered the anatomical geometry and wound configuration useful for basic training. The feedback indicated that material optimization is necessary before broader educational use.



Figure 7 Final sutured eyebrow prototype

3.2 Cost analysis and enviromental assessment

The material cost (Table 1) of the printed mould was low, amounting to approximately €1.95 for the anatomical eyebrow model. As the mould is designed for repeated use, this cost represents a one-time investment that can be distributed across multiple castings. The silicone consumption (Table 1) for a single eyebrow model was 113 g, corresponding to a material cost of approximately €2.94 per cast. Consequently, the total material cost of manufacturing the eyebrow prototype, including both the 3D-printed mould and the silicone cast, was approximately €4.89. For subsequent productions, the manufacturing cost would be limited primarily to the silicone material, resulting in a significantly lower unit cost per model.

Table 1 Material and silicone consumption and model cost

Model	Material amount [g]	Cost [euro]
Printed mould (PETG)	95.8	1.95
Silicone cast	113.00	2.94

The proposed workflow eliminates the use of animal or cadaveric tissues and therefore avoids the generation of biological waste. The reusable mould design further reduces material consumption during repeated production. The main environmental limitation is the use of silicone, which is chemically stable but not biodegradable. Nevertheless, the low material consumption, reusability of moulds, and local production process reduce waste compared with disposable or biologically derived training materials.

4 Discussion

The present study describes the development of silicone anatomical facial models for suturing training using 3D scanning, CAD modelling, additive manufacturing, and silicone casting. The proposed workflow demonstrates that anatomically shaped training models can be produced at low material cost while preserving the possibility of customization. This is consistent with previous studies showing that 3D printing can improve access to surgical training models and support task-specific simulation in medical education [12-15].

A key strength of the proposed approach is the integration of real anatomical geometry into the training model. Unlike flat suturing pads, anatomically shaped models provide spatial orientation and clinically relevant geometry, which may improve the realism of the training task. The eyebrow region was selected as the target anatomical area because it provides

CC BY NC

an appropriate environment for practising fundamental surgical suturing skills, including needle handling, wound-edge approximation, and knot tying. In addition, the eyebrow is a clinically relevant facial region frequently affected by lacerations requiring precise wound closure. The development of an anatomically shaped eyebrow model demonstrates the potential of additive manufacturing technologies to create customized training tools tailored to specific educational objectives in surgical training [12,14].

The results demonstrated the technical feasibility of the proposed digital and manufacturing workflow. The eyebrow mould was successfully fabricated using additive manufacturing and subsequently used for silicone casting. The resulting prototype accurately reproduced the intended anatomical geometry of the eyebrow region as well as the designed wound defect intended for suturing practice. The casting process yielded a functional silicone model suitable for basic surgical suturing exercises. The final prototype exhibited satisfactory anatomical fidelity and enabled the practice of wound-edge approximation, needle handling, and knot tying under anatomically relevant conditions. Minor manufacturing imperfections, including localized silicone leakage and air bubbles, were observed primarily on the posterior side of the model. However, these defects did not affect the anatomical surface or the functional area intended for training and therefore had no significant impact on the practical usability of the prototype.

The functional test confirmed that the prototype can be used for basic suturing practice but also revealed important material limitations. The initial silicone was too stiff and did not provide sufficiently realistic haptic feedback, needle penetration resistance, or wound-edge approximation. This finding is important because the educational value of a suturing simulator depends not only on anatomical geometry, but also on the mechanical similarity of the material to human tissue [16,18]. Previous studies have shown that artificial skin models should reproduce key biomechanical properties, including tensile behaviour, viscoelastic response, and resistance to tearing [16]. Therefore, further material optimization is necessary.

Although the material properties were not optimal, the anatomical design of the wound was positively evaluated. The tester reported that the wound depth and shape were more realistic than those of standard flat suturing pads. This suggests that geometric realism and material realism should be considered as complementary design requirements. In the present prototype, the geometric component was successful, whereas the material component requires further development. This finding supports the need for an iterative design strategy combining digital geometry optimization with experimental mechanical testing.

A major advantage of the proposed model is its low production cost. The material cost of a single silicone cast was substantially lower than the cost typically associated with commercial anatomically shaped trainers. In addition, the moulds are reusable, which further reduces the cost of repeated production. This makes the proposed workflow potentially suitable for educational environments with limited resources. Low-cost models may support repeated individual practice, which is considered important for the development of surgical skills [10,13].

The model also has environmental and practical advantages. It eliminates the need for animal or cadaveric tissue and therefore avoids ethical concerns, storage requirements, and biological waste. In contrast to biological models, silicone trainers are easier to store, handle, and reproduce. However, silicone is not biodegradable, and its long-term environmental impact should be considered. Reusable moulds and controlled material consumption partly reduce this limitation.

This study has several limitations. First, the functional evaluation was performed using only a single anatomical eyebrow model, which limits the ability to assess the applicability of the proposed methodology to other facial regions. Second, functional testing was conducted by a single medical student, and therefore the findings cannot be generalized to a broader population of users with different levels of surgical experience. Third, the mechanical properties of the fabricated silicone model were not experimentally characterized. Consequently, parameters such as tensile strength, puncture resistance, tear resistance, and elasticity were not quantitatively compared with reported values for human skin or synthetic training materials [16,18]. Finally, the model was not evaluated by experienced surgeons, and therefore its educational value, content validity, and clinical realism remain to be verified through expert assessment.

Future work should focus on the selection and testing of softer silicone elastomers with lower Shore A hardness and improved tear resistance. Multilayered casting could also be explored to better reproduce the structure of skin and subcutaneous tissue. In addition, larger-scale validation involving medical students and surgeons would allow assessment of construct validity and training effectiveness.

Overall, the proposed approach provides a feasible and low-cost method for producing customized silicone anatomical models for facial suturing training. Although the current prototype requires material and mould optimization, the results demonstrate the potential of combining 3D scanning, CAD modelling, additive manufacturing, and silicone casting for the development of accessible and anatomically relevant surgical training tools.

5 Conclusions

This study presented a workflow for the development of silicone anatomical facial models intended for surgical suturing training. The proposed approach combined 3D facial scanning, CAD modelling, additive manufacturing of casting moulds, and silicone casting to create anatomically representative training models of a selected facial region. The developed methodology enabled the creation of customized models containing clinically relevant defects suitable for

CC BY NC

practising wound closure techniques. The fabricated prototype demonstrated the feasibility of producing anatomically shaped suturing trainers using readily available manufacturing technologies and low-cost materials. In addition, the use of reusable 3D-printed moulds allows efficient and repeatable production of training models while maintaining a high degree of geometric customization. The presented approach provides an accessible alternative to commercially available training simulators and demonstrates the potential of combining digital anatomical data with additive manufacturing technologies for medical education. The results support the use of personalized silicone models as a promising platform for the development of practical surgical skills in a safe and controlled training environment.

Acknowledgement
The authors would like to acknowledge that this study was conducted as part of the bachelor thesis of Natália Antolová, who is also a co-author of this manuscript. This research was supported by the Slovak Research and Development Agency under the contract No. APVV-22-0340. This research was supported by project KEGA 054TUKE-4/2025 Use of CAx systems in prosthetic and orthotic practice.

References

[1] ELENDU, C., AMAECHI, D.C., OKATTA, A.U., AMAECHI, E.C., ELENDU, T.C., EZEH, C.P., ELENDU, I.D.: The impact of simulation-based training in medical education: A review, *Medicine*, Vol. 103, No. 27, e38813, pp. 1-14, 2024. https://doi.org/10.1097/MD.0000000000038813

[2] ROMANCENCO, A., SARATILA, I., ABABII, I., ROJNOVEANU, G., DANDARA, O., SPINEI, L.: Bridging theory and practice: enhancing medical education through simulation-based training methods, *Moldovan Journal of Health Sciences*, Vol. 11, No. 2, pp. 68-73, 2024. https://doi.org/10.52645/mjhs.2024.2.09

[3] SUN, W., JIANG, X., DONG, X., YU, G., FENG, Z., SHUAI, L.: The evolution of simulation-based medical education research: From traditional to virtual simulations, *Heliyon*, Vol. 10, No. 15, e35627, pp. 1-14, 2024. https://doi.org/10.1016/j.heliyon.2024.e35627

[4] CARDOSO, S., SUYAMBU, J., IQBAL, J., JAIMES, D.C.C., AMIN, A., SIKTO, J.T., VALDERRAMA, M., AULAKH, S.S., RAMANA, V., SHAUKAT, B., PATEL, T.: Exploring the role of simulation training in improving surgical skills among residents: A narrative review, *Cureus*, Vol. 15, No. 9, e44654, 2023. https://doi.org/10.7759/cureus.44654

[5] MURPHY, G., KHAN, M.A., LATHIF, A., PREDDY, J.: A banana a day keeps wound failure away: comparing the utility of fruit, pig, and synthetic skins for suturing practice, *Medical Journal of Australia*, Vol. 215, No. 11, pp. 536-540, 2021. https://doi.org/10.5694/mja2.51347

[6] GONZÁLEZ-NAVARRO, A.R., QUIROGA-GARZA, A., ACOSTA-LUNA, A.S., SALINAS-ALVAREZ, Y., MARTÍNEZ-GARZA, J.H., DE LA GARZA-CASTRO, O., GUTIERREZ-DE LA O, J., DE LA FUENTE-VILLARREAL, D., ELIZONDO-OMAÑA, R.E., GUZMAN-LOPEZ, S.: Comparison of suturing models: the effect on perception of basic surgical skills, *BMC Medical Education*, Vol. 21, 250, pp. 1-11, 2021. https://doi.org/10.1186/s12909-021-02692-x

[7] JEFFERSON, I.S., ROBINSON, S., SURPRENANT, D., WHITTINGTON, A., ARSHANAPALLI, A., TUNG-HAHN, E., JOYCE, C., MOY, L., LEE, K., O'BRIEN, E., TUNG, R., ALAM, M.: Surgical training tools for dermatology trainees: porcine vs. synthetic skin for excision and repair, *Archives of Dermatological Research*, Vol. 313, pp. 793-797, 2021. https://doi.org/10.1007/s00403-020-02181-z

[8] BLAU, J.A., SHAMMAS, R.L., ANOLIK, R.A., AVASHIA, Y.J., KRUCOFF, K.B., ZENN, M.R.: Does Realism Matter? A Randomized Controlled Trial Comparing Models for Medical Student Suture Education, *Plastic and Reconstructive Surgery-Global Open*, Vol. 8, No. 4, e2738, 2020. https://doi.org/10.1097/GOX.0000000000002738

[9] SHAHREZAEI, A., SOHANI, M., TAHERKHANI, S., ZARGHAMI, S.Y.: The impact of surgical simulation and training technologies on general surgery education, *BMC Medical Education*, Vol. 24, 1297, pp. 1-15, 2024. https://doi.org/10.1186/s12909-024-06299-w

[10] ALMEIDA, N.R.C., BRAGA, J.P., BENTES, L.G.B., LEMOS, R.S., FERNANDES, M.R.N., ANDRADE, G.L., MENDONÇA DE ARAÚJO, V.M., DOS SANTOS, D.R., YASOJIMA, E.Y.: Low-cost suture simulator to gain basic surgical skills, *Acta Cirúrgica Brasileira*, Vol. 38, e384223, 2023. https://doi.org/10.1590/acb384223

[11] GALLAGHER, P., BISHOP, N., DUBROWSKI, A.: Investigating the perceived efficacy of a silicone suturing task trainer using input from novice medical trainees, *Cureus*, Vol. 12, No. 1, e6612, 2020. https://doi.org/10.7759/cureus.6612

[12] ZHU, Z., AMADI, S.M., MAO, J., ZHOU, M., XIA, M., PARIKH, N.J., HU, J., WANG, Z.: A randomized cohort study on the use of 3D printed models to enhance surgical training in suturing techniques, *Scientific Reports*, Vol. 15, 636, 2025. https://doi.org/10.1038/s41598-024-84887-y

[13] LANE, A.C., BLACK, J.S.: Modeling Medical Education: The Impact of Three-Dimensional Printed Models on Medical Student Education in Plastic Surgery, *Journal of Craniofacial Surgery*, Vol. 31, No. 4, pp. 1018-1021, 2020. https://doi.org/10.1097/SCS.0000000000006567

[14] CÔTÉ, V., SCHWARTZ, M., ARBOUIN VARGAS, J.F., CANFAROTTA, M.W., KAVANAGH, K.R., HAMDAN, U., VALDEZ, T.A.: 3-Dimensional printed haptic simulation model to teach incomplete cleft palate surgery in an international setting, *International Journal of Pediatric Otorhinolaryngology*, Vol. 113, pp. 292-297, 2018. https://doi.org/10.1016/j.ijporl.2018.08.016

[15] BOYAJIAN, M.K., LUBNER, R.J., ROUSSEL, L.O., CROZIER, J., RYDER, B.A., WOO, A.S.: A 3D printed suturing trainer for medical students, *The Clinical Teacher*, Vol. 17, No. 6, pp. 650-654, 2020. https://doi.org/10.1111/tct.13176

[16] BOGDANOV, T., HIKOV, T., YANEV, K., PAPADAKIS, K., MILEVA-POPOVA, R.D.: Development and Mechanical Characterization of Artificial Skin for Surgical Suture Training: Tensile Strength and Viscoelastic Properties Compared to Human Skin, *Cureus*, Vol. 17, No. 3, e81123, 2025. https://doi.org/10.7759/cureus.81123

[17] ZARE, M., GHOMI, E.R., VENKATRAMAN, P.D., RAMAKRISHNA, S.: Silicone-based biomaterials for biomedical applications: Antimicrobial strategies and 3D printing technologies, *Journal of Applied Polymer Science*, Vol. 138, No. 38, 50969, 2021. https://doi.org/10.1002/app.50969

[18] NAVINDARAN, K., KANG, J.S., MOON, K.: Techniques for characterizing mechanical properties of soft tissues, *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 138, 105575, pp. 1-12, 2023. https://doi.org/10.1016/j.jmbbm.2022.105575

[19] BALAJI, A., MAKAM, R., BALAJI, A., MOKTARI, A., O'REGAN, D.: Realising Ideal Home Practice Models for Surgical Skill Development, *Journal of Surgery and Research*, Vol. 8, No. 3, pp. 437-441, 2025. https://doi.org/10.26502/jsr.10020469

Review process
Single-blind peer review process.