3D Printing in Medicine

RESEARCH

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Evaluating the value of 3D-printed bone models with fracture fragments connected by flexible rods for training and preoperative planning

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Abstract

Background The emergence of 3D printing has revolutionized medical training and preoperative planning. However, existing models have limitations, prompting the development of newly designed flexible 3D-printed bone fracture models.

Methods The designed flexible 3D-printed bone fracture models were evaluated by 133 trauma surgeons with different levels of experience for perceived value as educational tool or as preoperative planning tool.

Results The models allowed drilling and showed resistance to manipulation and sterilization. Surgeons found the flexible model helpful for teaching and planning the reduction of fractures, planning and simulating osteosynthesis, understanding fractures, visualizing fractures, and planning surgical approaches.

Conclusions Flexible 3D-printed bone fracture models offer a dynamic and realistic approach to understanding complex fractures, potentially improving surgical training and preoperative planning.

Keywords 3D-printed bones, 3D printing, Surgical education, Preoperative planning, Simulation of reduction and osteosynthesis

Background

The advent of 3D printing has enabled the production of accurate, patient-specific anatomical models that can aid surgical training and surgical planning [1–3]. The addition of 3D-printed bone models during medical training enhances the understanding of bone spatial anatomy and fracture classification for spine and pelvis fractures [4, 5] and radius fractures [6]. 3D-printed anatomical bone models have been increasingly used in preoperative planning, especially for articular fractures, with the aim of helping with the choice of surgical approach and fracture reduction plan [7, 8].

Currently, 3D models are produced starting from medical imaging data, with the most common being computed tomography (CT) scanning followed by magnetic resonance imaging (MRI) [2]. The images are subsequently segmented and refined using commercially available software to create a printable file [2]. Segmentation is the key step for ensuring the fidelity and detail of the model, which can be compromised by excessive filling of gaps and oversimplification [8, 9]. There are several printing techniques and printing materials, each of which has its own benefits and weaknesses. At present, in

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most 3D-printed fracture models, the fragments are fixed through connecting structures known as "struts" (Fig. 1a and b black arrows) [7, 10].

There are also more dynamic models in which a magnetic connection allows separation of the distal tibia and fibula; however, the displaced bone fragments are still fixed [8]. These 3D-printed fracture models allow the identification of the exact position of specific fracture fragments; however, they do not allow the movement of the fragments or the practice of reduction or osteosynthesis. There are also 3D-printed fracture models with free fracture fragments. The advantage of these models is that they allow us to look every side of the fragments and to assemble the fragments again to understand therapeutic options, surgical approaches and screw placement [11]. The disadvantage of freely moving fragments is that any realistic connection or haptic counterforce is missing. For these reasons, we decided to design and evaluate a new type of 3D-printed bone model with fracture fragments connected by flexible rods, which we call "tentacles". In this article, we describe this new design and the first evaluation provided by 133 trauma surgeons.

Materials and methods

3D object modeling

Segmentation, the process of digitally defining fragments and fracture lines and boundaries, was performed, and 3D files of the scanned fractures were provided in OBJ format by the Rymasis Group from their database of imaged pre-fractured human specimens [12].

The connecting rods of the fragments, which we called "tentacles", were then designed using CAD (AutoCAD, Autodesk, San Francisco, CA, USA). The tentacles are slender rods of varying thickness made of the same material as the bone fragments themselves. The design parameters of the rods included both the geometry (rectangle, circle, tube, oval, etc.) and the dimensions (e.g., diameter) as well as the length of the rods. The relevant formulas for determining the tentacle design included the maximum allowable stress in the outer layer of the tentacle base (σ_max), the area moment of inertia based on the cross section of the tentacle, and the stiffness of a beam based on its length (classical bending of a unilaterally restrained flexural beam). Therefore, sufficient parameters are available for sizing tentacles for almost any application. Due to their thinness, they can be significantly deformed without reaching the maximum load limit of the additive manufacturing material used, resulting in their tentacle-like behavior. It is also possible to increase the number of tentacles per bone fragment to provide the expected degrees of freedom based on the experience of the testing surgeons.

The tentacle design has been submitted for patent application by Marenco AG and Dankward Höntzsch. Application number: PCT/DE2022/100240 (WO2022DE100240).

Flexible 3D print production

After the printable file was prepared, an optimization step to maximize the usage of the printing job needed to be performed. The spatial positioning of the 3D model allows for the printing of an average of 56 models for each printing job. Printing was performed using a multi jet fusion printer (HP MJF 4200 MJF 4200; HP, Palo Alto, CA, USA) and polyamide 12 powder (HP 3D High Reusability PA 12; HP, Palo Alto, CA, USA).

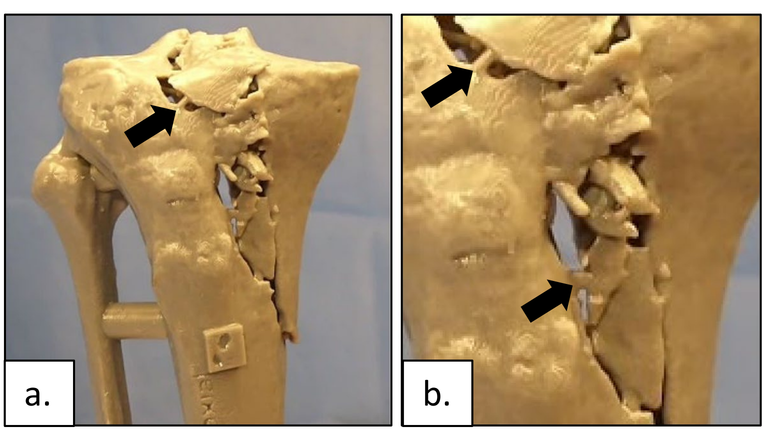

Fig. 1 State-of-the-art 3D-printed fracture model. **a** Currently available state-of-the-art 3D-printed fracture model of a tibia head fracture. **b** Magnified area. The black arrows point at the struts

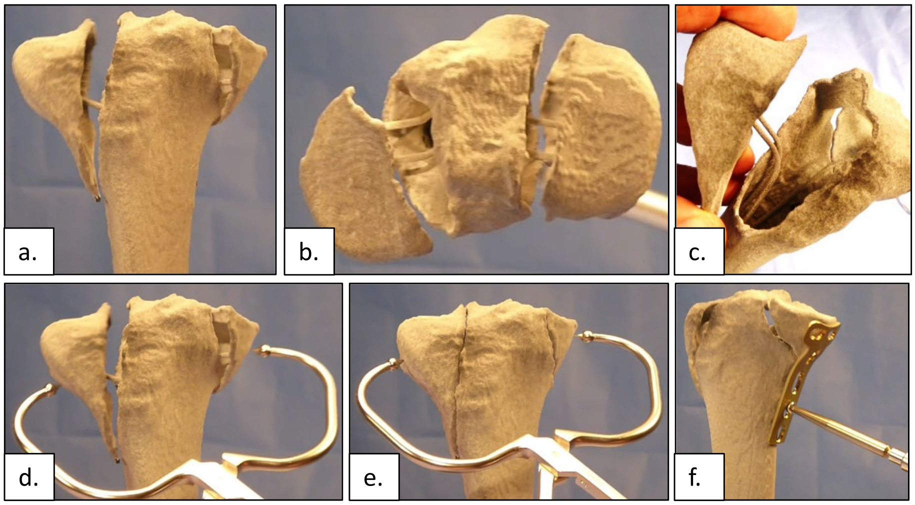

Fig. 2 Flexible 3D-printed model prototypes of a bicondylar tibia head fracture. **a** Anterior view of a bicondylar tibia head fracture with flexible connected fragments called tentacles. **b** Upper view. **c** Internal view and particular view of the flexible long and curved tentacles. **d** Simulation of fracture reduction. Prereduction and **e** Postreduction. **f** Simulation of an osteosynthesis with a plate

Evaluation of the models: questionnaire development, delivery, and data analysis

A questionnaire was designed to investigate the surgeon's perceived value of the new flexible 3D fracture models as an educational tool for course participants and faculty or as a preoperative planning tool.

Author Dankward Höntzsch showed the new flexible 3D printed models and provided a QR code directing to an online questionnaire (SurveyMonkey, San Mateo, California, United States) available in Appendix 1 at the following events:

– Master Course AO Trauma—Fracture Challenge: How Masters Manage Tibial Plateau Fractures September 22–23, 2022 in Cologne, Germany

  In this course, conventional 3D-printed fracture models of the tibia head were used as preoperative planning tools for practical exercise on pre-fracture human specimens. The participants were subsequently introduced to the new flexible 3D-printed models.

– AO Davos Courses, December 04-16, 2022 in Switzerland.

  In this context, a permanent exhibition booth was organized, and specific time slots were allocated for focus demonstrations, explanations, and discussions over 6 days. For comparative analysis, a conventional 3D-printed fracture model with fixed fracture fragments was showcased (Fig. 1a and b).

Ethical approval

According to the Ethics Committee of the Canton of Zurich, this study did not require ethical committee authorization (Req-2024-00906). On the survey, we included the following statement of purpose, which disclosed our intended use of the data: "The information you provide will be anonymized and made available in aggregate form."

Fig. 3 Drilling and screwing are similar to those of other artificial bone models commonly used

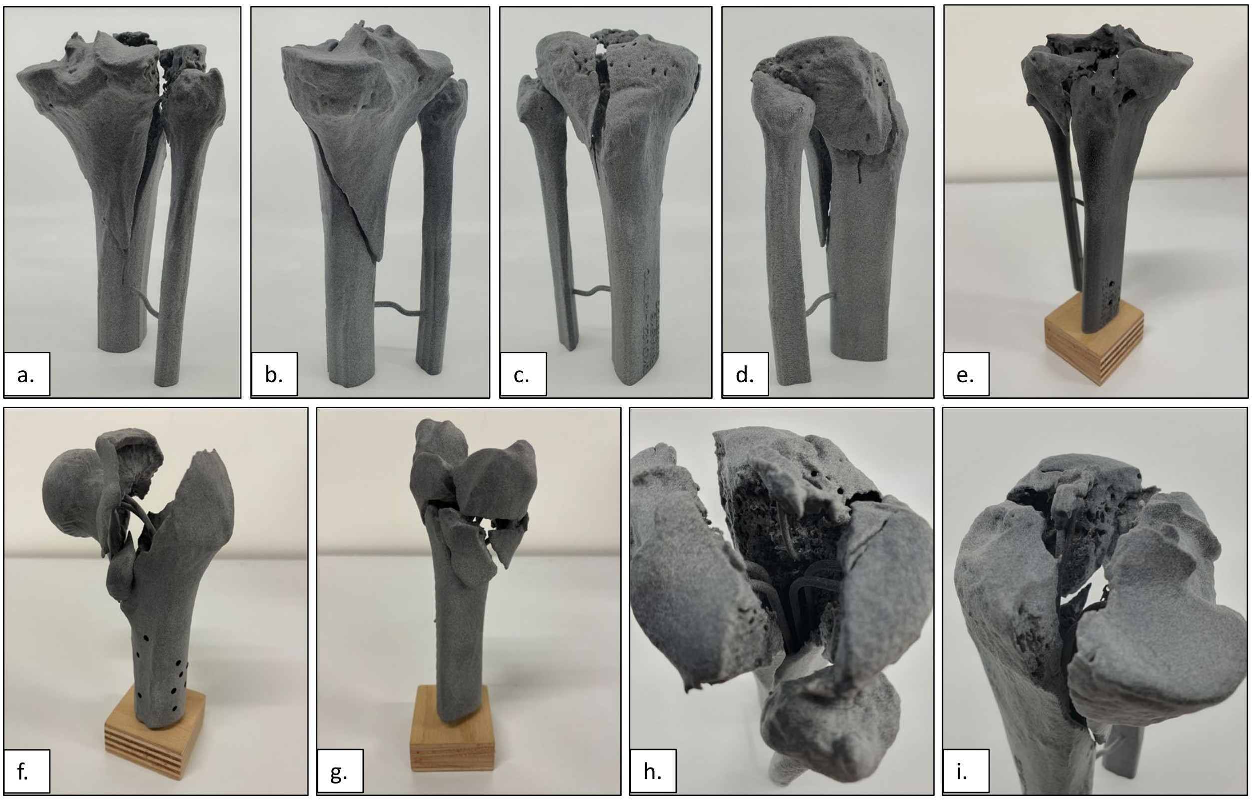

Fig. 4 Samples of available flexible 3D-printed fracture models. **a**-**e** Tibia head fractures. **f** Trochanteric fracture. **g** Pilon/distal tibia fracture. **h**-**i** Internal structure with the spongiosa

Results

Flexible 3D-printed models

The design of the tentacles was adapted and tested to match different properties and behaviors of the fragments, resistance to movement, haptic feeling, and spring properties (Fig. 2a-c). The models were also tested for fracture reduction (Fig. 2d and e) and osteosynthesis (Fig. 2f).

We also tested the response to drilling. The PA12 material did not generate high temperatures and did not melt during drilling. The screws could be inserted in a realistic way, and the holding force for the threads was good (Fig. 3).

For the final evaluation, we generated several models, including tibial head fractures in 12 variations; pilon tibial, distal femur, and proximal femur pertrochanteric fractures, and proximal humeral head fractures (Fig. 4).

We ultimately tested the durability of the flexible models when multiple manipulations were performed by several surgeons. Despite intensive use and experiencing instances of being dropped, the models were demonstrated to be durable and resistant. The models performed very well after consecutive cycles in the dishwasher and after sterilization.

Flexible 3D-printed model evaluation

The evaluation of the models was collected in the context of a Master Course AO Trauma—How Masters Manage Tibial Plateau Fractures (Fig. 5) and the AO Davos Courses 2022.

The first feedback was obtained from 32 experienced German surgeons (60% graduated more than 15 years

Fig. 5 Flexible 3D fracture model shown during a practical exercise on pre-fractured human specimens. Master Course AO Trauma—Fracture Challenge: How Masters Manage Tibial Plateau Fractures September 22–23, 2022 in Cologne, Germany

ago; Fig. 6a, b) attending the course *Fracture Challenge: How Masters Manage Tibial Plateau Fractures*. To evaluate their overall familiarity with 3D-printed fracture models, we asked how often they previously used them for training and for preoperative planning. 75% of the surgeons used 3D-printed models for training purposes (Fig. 6c) and 47% for preoperative planning (Fig. 6d). To test their perception of the value of 3D-printed fracture models, we asked whether the use of 3D-printed models would help them with surgical training (91% yes Fig. 6e) or preoperative planning (83% yes Fig. 6f). We then asked which type of 3D-printed model would help the most with surgical training or preoperative planning. 50% of surgeons perceived an advantage of the flexible model over the fixed model for training, while 41% were unsure (Fig. 6g). For preoperative planning, 47% preferred the flexible model, 31% were unsure (Fig. 6h). 82% of surgeons considered flexible models appropriate for practicing reduction, and 75% considered flexible models appropriate for osteosynthesis. 60% of surgeons found flexible models realistic or very realistic.

We administered the same questionnaire in an international setting in the context of the AO Davos Courses, December 04–16, 2022, and we received 101 responses from surgeons from various backgrounds and training levels. The responding surgeons practiced in 28 countries (Switzerland 25, Germany 10, Australia 7, 4 for the USA, India and Denmark; 3 for Austria, the Netherlands, Saudi Arabia, Spain; 2 for Brazil, Iraq, Ireland, Korea South, Mexico; 1 from Belgium, Chile, Colombia, France, Greece, Jordan, Kuwait, Malaysia, Pakistan, Slovenia, Sri Lanka, Thailand, Turkey). 38% were residents, while the rest were more experienced surgeons, with 46% having more than 15 years

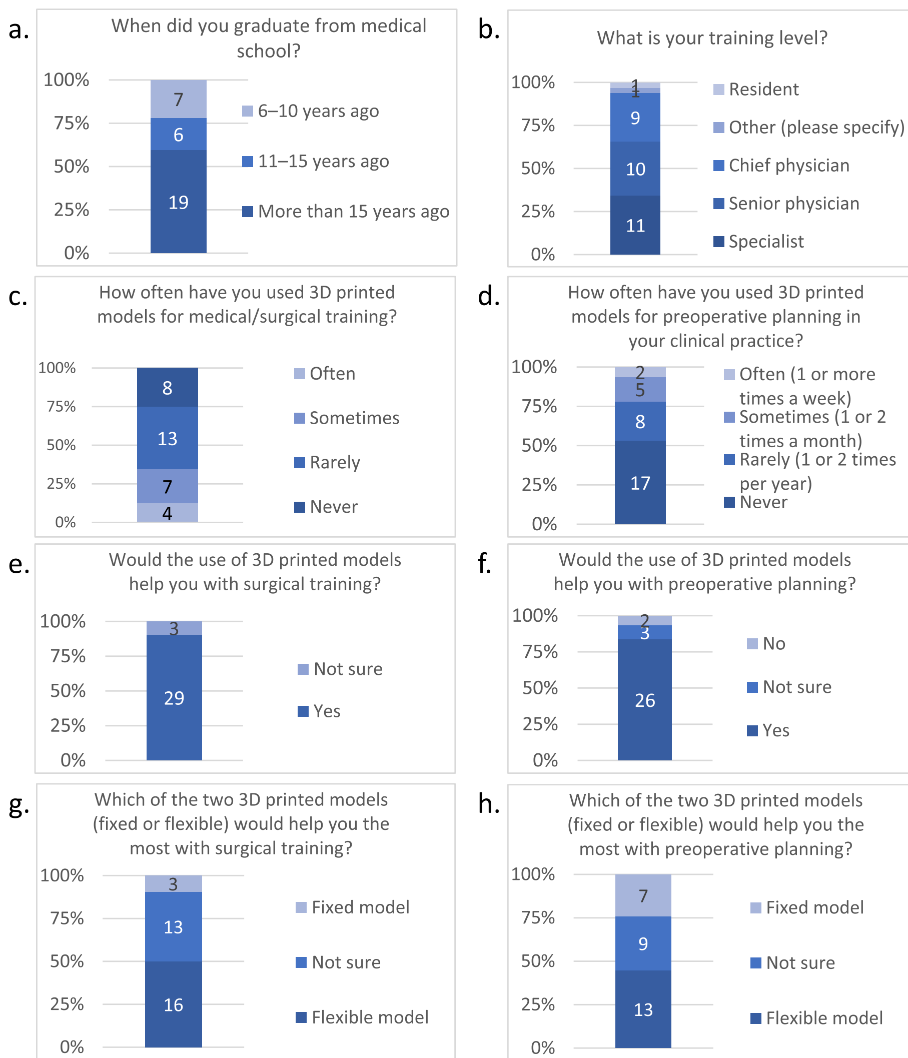

Fig. 6 Evaluation results collected at the Master Course AO Trauma—Fracture Challenge: How Masters Manage Tibial Plateau Fractures September 22–23, 2022 in Cologne, Germany. *N* = 32

of experience (Fig. 7a and b). 53% of surgeons used 3D-printed models for training purposes (Fig. 7c) and 51% for preoperative planning (Fig. 7d). 91% affirmed that the models would help them with surgical training (Fig. 7e) and 94% with preoperative planning (Fig. 7f). 88% of surgeons perceived an advantage of the flexible model over the fixed model for training, while 10% were unsure (Fig. 7g). For preoperative planning, 89% preferred the flexible model, and 8% were unsure (Fig. 7h). 98% of surgeons consider flexible models appropriate for practicing reduction and 97% for osteosynthesis. 82% of surgeons found flexible models realistic or very realistic. Surgeons found the flexible model helpful in a preoperative planning context for planning fracture reduction, planning and simulating osteosynthesis, understanding the fracture, visualizing the fracture, and planning the approach (Fig. 7i).

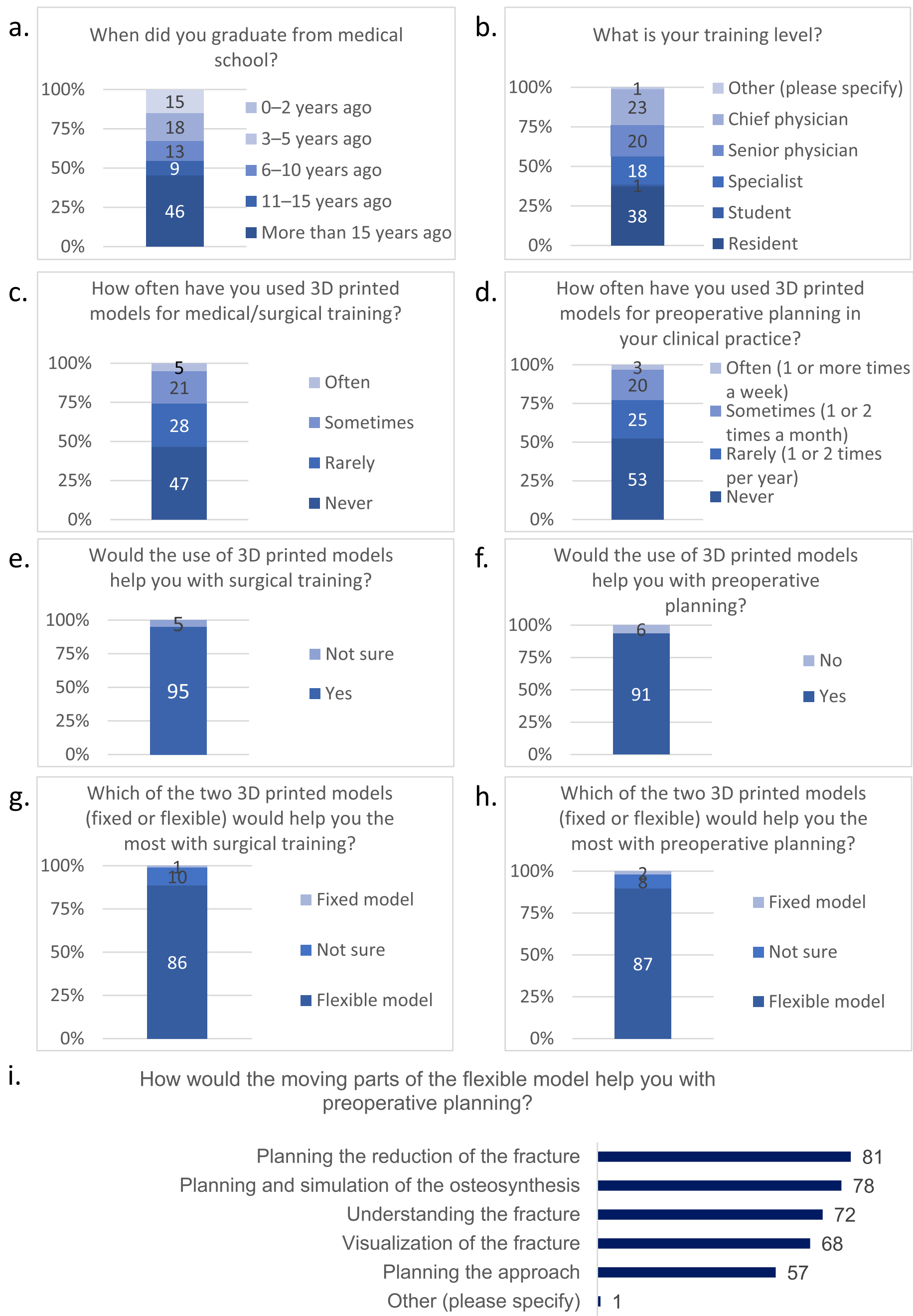

Fig. 7 Evaluation results collected at AO Davos Courses, December 04–16, 2022. $N = 101$

Fig. 8 Tibial plateau fracture 3D-printed flexible model embedded in a foam model. The simulation of access, visualization of the fracture, reduction and osteosynthesis can be performed very realistically

Discussion

In this article, we described and evaluated a new design of 3D-printed fracture bone models with flexible tentacles that allows fracture fragment movement. The models allow drilling and show resistance to manipulation and sterilization. Surgeons found the flexible model helpful for teaching and planning the reduction of fractures, planning and simulating osteosynthesis, understanding fractures, visualizing fractures, and planning surgical approaches.

We maintained the evaluation datasets obtained for the two events separately due to possible confounding factors created by the course environment. In fact, in the master's course, standard fixed 3D-printed models were utilized during practical exercises as a preoperative planning tool for pre-fractured human specimens. This approach allowed the participants to appreciate the advantages of using fixed fracture models and to compare them to the newly designed flexible models. In this course, the percentage of surgeons preferring the flexible model over the fixed model was lower than that of surgeons participating in the AO Davos Courses (approximately 50% versus 90%), and a large proportion (41% and 38%) felt that both models could be useful for training and preoperative planning (Fig. 7f). This is probably because surgeons experienced the benefits of fixed models, allowing to identify the exact spatial localization of the fragments [8], but also appreciated the benefits of the new flexible model. Overall, flexible 3D-printed models were preferred over fixed models.

Interestingly, among our sample of 133 trauma surgeons, more than 50% previously used 3D-printed models for surgical training or preoperative planning. This is consistent with the growing use of these models [1, 13, 14] and the derived benefits. Notably, the use of 3D-printed bone model fractures in the preoperative planning of comminuted humeral intercondylar fractures has been demonstrated to reduce the operation duration, blood loss volume and number of intraoperative fluoroscopy images [10].

The flexible 3D-printed models were designed to allow fracture fragment visualization and practice reduction that was not possible to obtain with the models previously available. This approach is especially relevant for intraarticular fractures where anatomic reconstruction of the articular surface, stable internal fixation and early exercise are the keys for successful recovery. The tibial plateau fractures can be seen as an exemplary region where the movement of the fragments could help to exemplify the practical benefits of a specific surgical technique such as the posterolateral approach in tibial plateau fractures [15]; therefore, the advantages of the flexible version can be used particularly effectively (Fig. 8).

3D-printed models are not limited to long bones but are currently used for spine [3] and cranio-maxillofacial bones [2, 16]. Therefore, future developments of flexible 3D-printed models might consider extraosseous solutions of tentacles for those types of bones.

Limitations

The limitations of this study include the small sample size, participant selection bias and the presence of external factors that could influence participants' responses, such as their prior exposure to similar models and individual learning preferences.

Conclusions

Flexible 3D-printed bone models address the limitations of traditional fixed models and fully mobile models by combining movements of fracture fragments with structural stability. These models show potential in transforming surgical training and preoperative planning by providing a more dynamic and realistic approach to understanding complex fractures. As technology continues to advance and costs decrease, these models may become a standard in medical education and clinical practice.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s41205-025-00250-5.

Supplementary Material 1.

Acknowledgements

We would like to thank Raffael Heierli and Rolf Spichtig from Marenco AG® for their contribution to the design and production of the 3D bone models and Karsten Engel from the Rimasys Group for technological support.

Authors' contributions
MG work conception and design, data analysis, data interpretation, article drafting; DH work conception and design, data acquisition, article drafting; BA work conception, manuscript revision; SC work conception, manuscript revision.

Funding
This work was supported by the AO innovation funding.

Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
According to the Ethics Committee of the Canton of Zurich, this study did not require ethical committee authorization (Req-2024–00906). On the survey, we included the following statement of purpose, which disclosed our intended use of the data: "The information you provide will be anonymized and made available in aggregate form. The data will be used for research purposes."

Consent for publication
Not applicable.

Competing interests
Dankward Höntzsch is a retired professor of trauma surgery at the BG Trauma Center and University of Tübingen and a long-standing AO and AO Technical Commission member. Bedran Atici is a development engineer at Marenco AG®, the company that is in process to patent this innovative 3D model design together with Dankward Höntzsch. The other authors declare no conflicts of interest.

Received: 8 July 2024 Accepted: 8 January 2025
Published online: 15 January 2025

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