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Are Three-Dimensional Printed Models Useful for Preoperative Planning of Tibial Plafond Fractures?

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ABSTRACT

Computed tomography (CT) scans with 3-dimensional (3D) reconstruction are the gold standard of imaging for complex fractures. However, visualising CT imaging can be challenging. With increasing access to 3D printing, we postulate that life-sized 3D models can better assist in visualising CT images, aiding preoperative planning of tibial plafond fractures. 3D models of 3 tibial plafond fractures of differing complexities were printed. We approached surgeons in our institution who manage tibial plafond fractures to complete a questionnaire on preoperative planning of the cases based on CT scans. We then examined whether analysing the 3D models after that changed the plan. This included ratings on the usefulness, accuracy, and ease of use of the models. Six surgeons participated in the study. In the simple fracture model, median usefulness was graded as 4.5 (range minimum to maximum: 0 to 7), accuracy 8 (4 to 10), and ease of use 9 (7 to 10) with 0 being the lowest and 10 being the upper limit of how useful, accurate, or easy to use the models were. For the intermediate fracture, median usefulness was 6.5 (2 to 8), accuracy 7.5 (3 to 10), and ease of use 8.5 (7 to 10). For the complex fracture, median usefulness was 6 (1 to 9), accuracy 7.5 (1 to 9), and ease of use 8.5 (0 to 9). We attribute these poorer scores to difficulty in processing the scans, resulting in less accurate printing of the many fragments in complex impacted fractures. In conclusion, 3D-printed models are easy to use and accurate in preoperative planning of tibial plafond fractures. Most surgeons believe that 3D models and CT scans combined were more useful than CT scans alone.

Computed tomography (CT) scan with 3-dimensional (3D) reconstruction is considered the gold standard imaging modality for complex fractures. However, visualising CT 3D imaging can be challenging, especially for less experienced surgeons. Even with a 3D reconstruction, the interior of the fracture can be difficult to appreciate.

3D printing is increasingly becoming commonplace with the availability of affordable printers and simple software. Orthopaedic surgery is 1 area in which this technology is being used, ranging from the printing of bone models to actual personalised implants. 3D bone models have been used in preoperative planning, implant contouring, surgical rehearsal, and medical education (1,2).

With the increasing availability of 3D printing technology, we postulate that 3D-printed fracture models can offer improved assistance in preoperative planning. We decided to focus on tibial plafond fractures because they are usually complex and comminuted injuries resulting from high-energy trauma (3–5). The keys to good outcome in these fractures are the restoration of the articular surface and alignment of the mechanical axis; hence the importance of preoperative planning.

We hypothesised that 3D fracture models are more helpful than solely using CT scans in the preoperative planning of tibial plafond fractures. Our primary objective was to assess whether the models provided information that would change the initial surgical plans made based on CT scans. Our secondary aim was to assess the 3D models' usefulness, accuracy, and ease of use.

Materials and Methods

Institutional review board ethical approval was obtained before study initiation. Three tibial plafond fractures of differing complexities (simple, intermediate, and complex) were identified from our trauma database. The complexity is based on the Müller AO classification system group 43, with simple being a C1 type, intermediate a C2 type, and complex a C3 type (6). We assessed how the severity and degree of comminution of the fractures can affect the accuracy, ease of use, and usefulness of the 3D models. The number of models printed also took into consideration time constraints in administering the survey, to not overburden the surgeons.

CT scans of these fractures were processed using Materialise's Interactive Medical Image Control System (Mimics software; Materialise, Leuven, Belgium). The "threshold" function was used to separate soft tissue to isolate only the bony structures. This is possible because bone has a different gray-value (Hounsfield unit in CT scan) than soft tissue.

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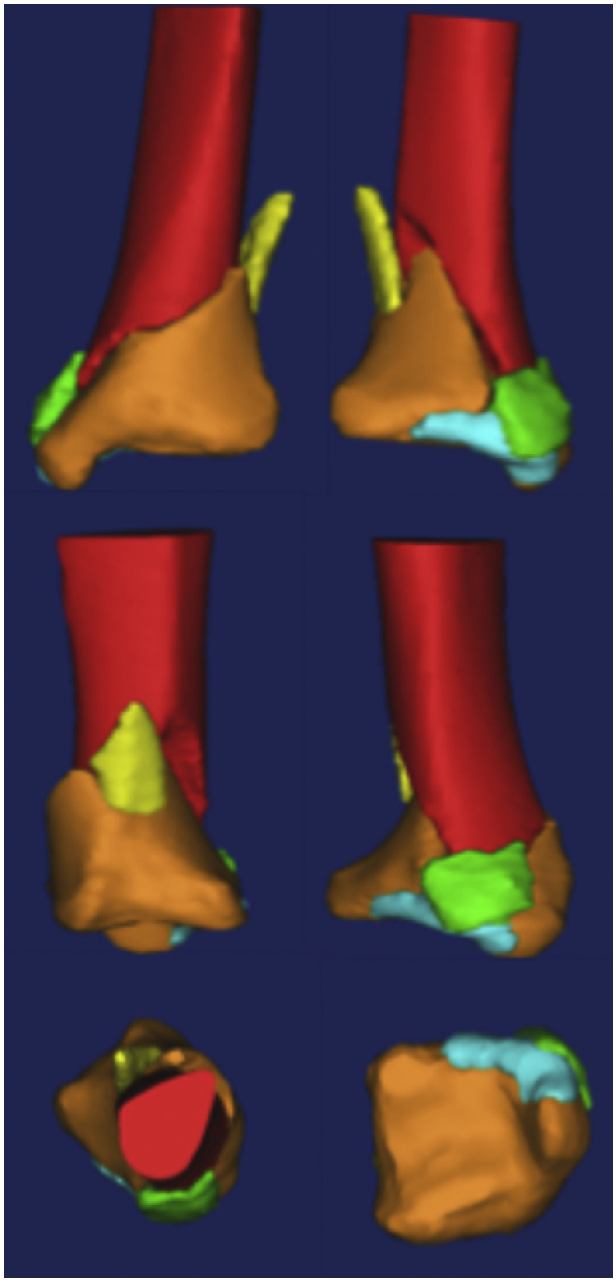


Fig. 1. Fracture segmentation of the complex case using Mimics software (Materialise, Leuven, Belgium).

To separate (segment) individual fragments for printing, the "region growing" function was used that connects all volumetric pixels (voxels) within the threshold that are physically connected to the initially selected voxel. However, because of the impaction of the fragments, especially in the complex highly comminuted fracture, some of the fragments had to be isolated manually (Fig. 1).

The isolated fragments were then converted into a 3D model using the "calculate 3D" function before being exported into the Standard Tessellation Language format for printing. Synthetic models were printed using a Fabbox 3D printer (FabboX, Singapore) and acrylonitrile butadiene styrene (ABS) material (Figs. 2–4).

Numerous 3D printer models are available on the market. These can range from simple consumer printers to high-end industrial printers that can print with various materials including metal. The average cost of a consumer printer able to generate the anatomical fracture models used in our study is approximately $2500. The cost of the ABS material is approximately $35 per kilogram, and each model used ~100 grams, for a cost of $3.50 for the material alone.

We approached surgeons who manage tibial plafond fractures in our institution to complete a questionnaire on preoperative planning of the 3 cases based on CT scans. The recruitment period was from March 2016 to March 2017. The questionnaire was developed considering the processes in managing tibial plafond fractures (Fig. 5). This began with the surgeon's preoperative plans based on their assessment of the radiograph and CT scans. They were first shown radiographs and CT scans for each of the cases and asked to create a plan that included the surgical approach, implants of choice, and surgical techniques. After that, they were given the 3D models to examine and re-evaluate their initial plans made using the CT scans. Any change in the preoperative plan was noted.

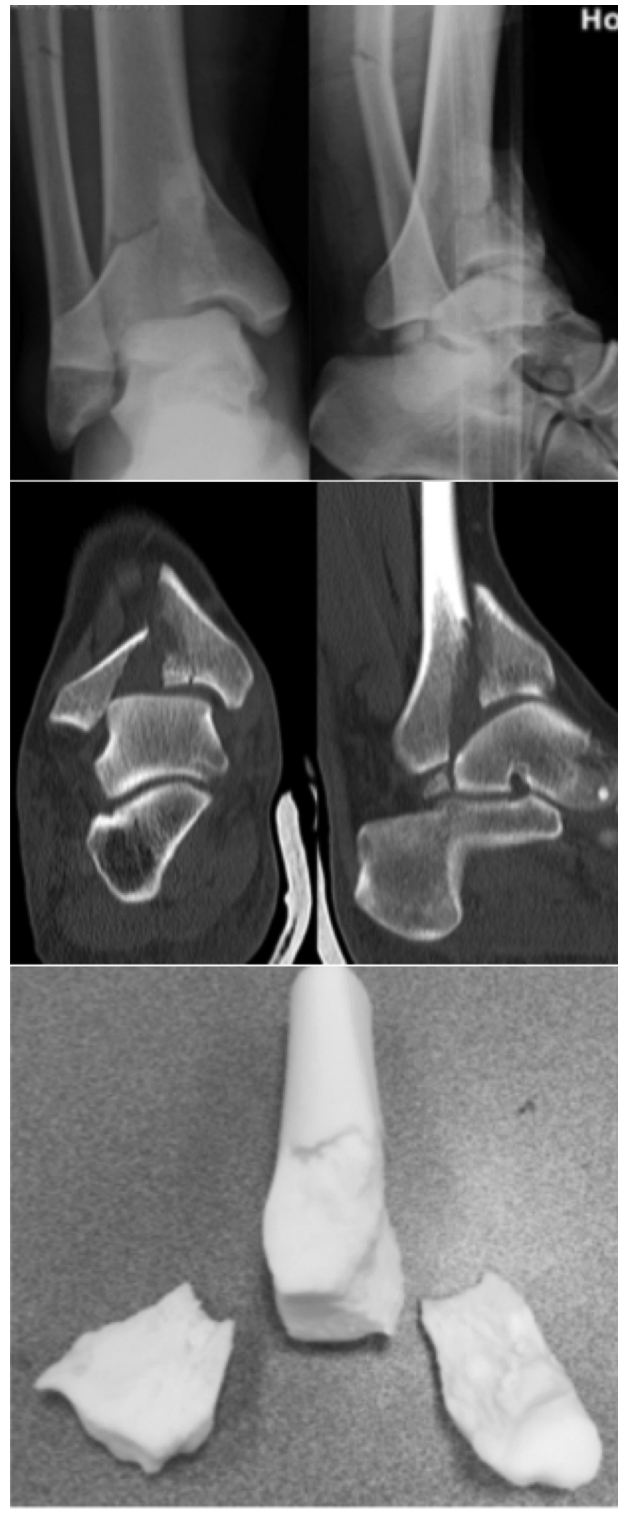


Fig. 2. Radiographs, CT imaging, and 3D model of the simple case.

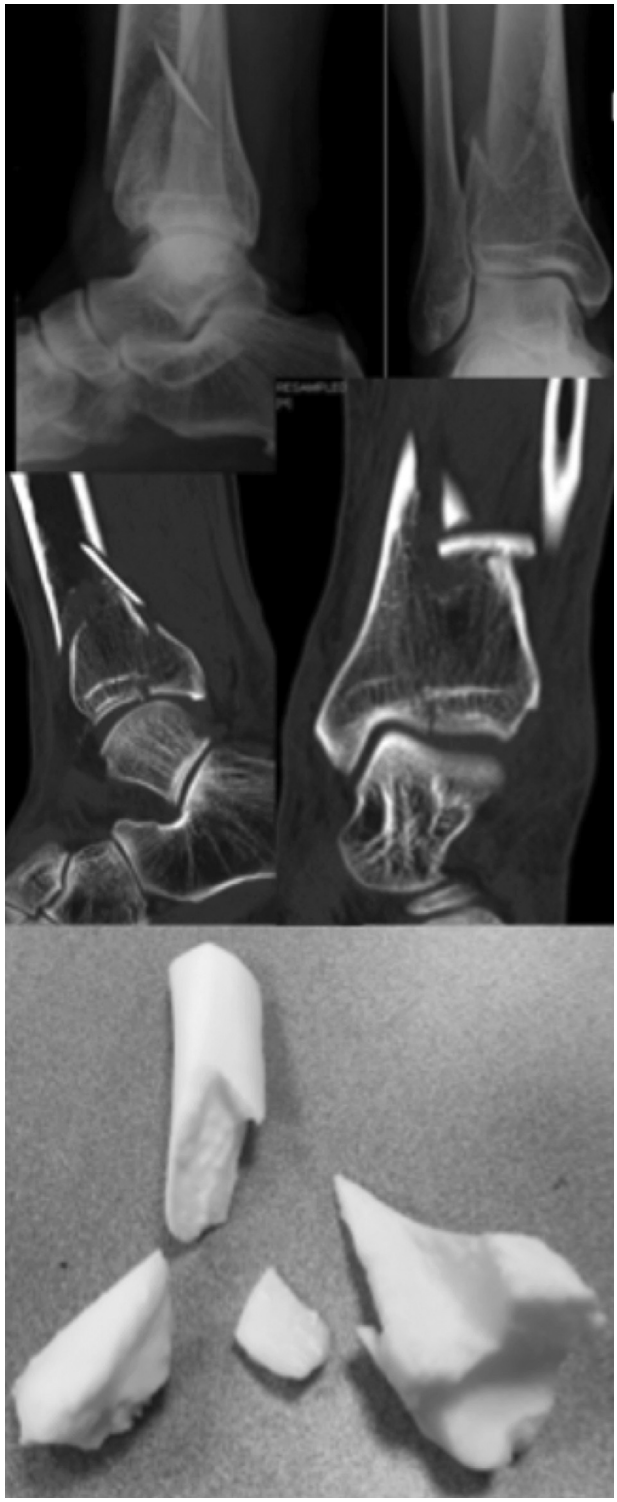


Fig. 3. Radiographs, CT imaging, and 3D model of the intermediate case.

The assumption was that the changes were attributed to the 3D model providing additional information compared to the CT scans alone.

The next part of the questionnaire were open-ended questions on the benefits of the 3D models and an 11-point Likert scale on their usefulness, accuracy, and ease of use. The rating started with 0 being the lowest and 10 being the upper limit of how useful, accurate, or easy to use the models were. The higher the score, the better the models were in each respective category. We could not identify a universally-accepted reliable and validated Likert scale rating 3D models in the literature. We decided on an odd-number 11-point Likert scale to maximise reliability, validity, and respondent preference (7). Respondents were also asked open-ended questions about the benefits of the 3D model and whether the combination of 3D model and CT scan was more useful than the CT scan alone in preoperative planning.

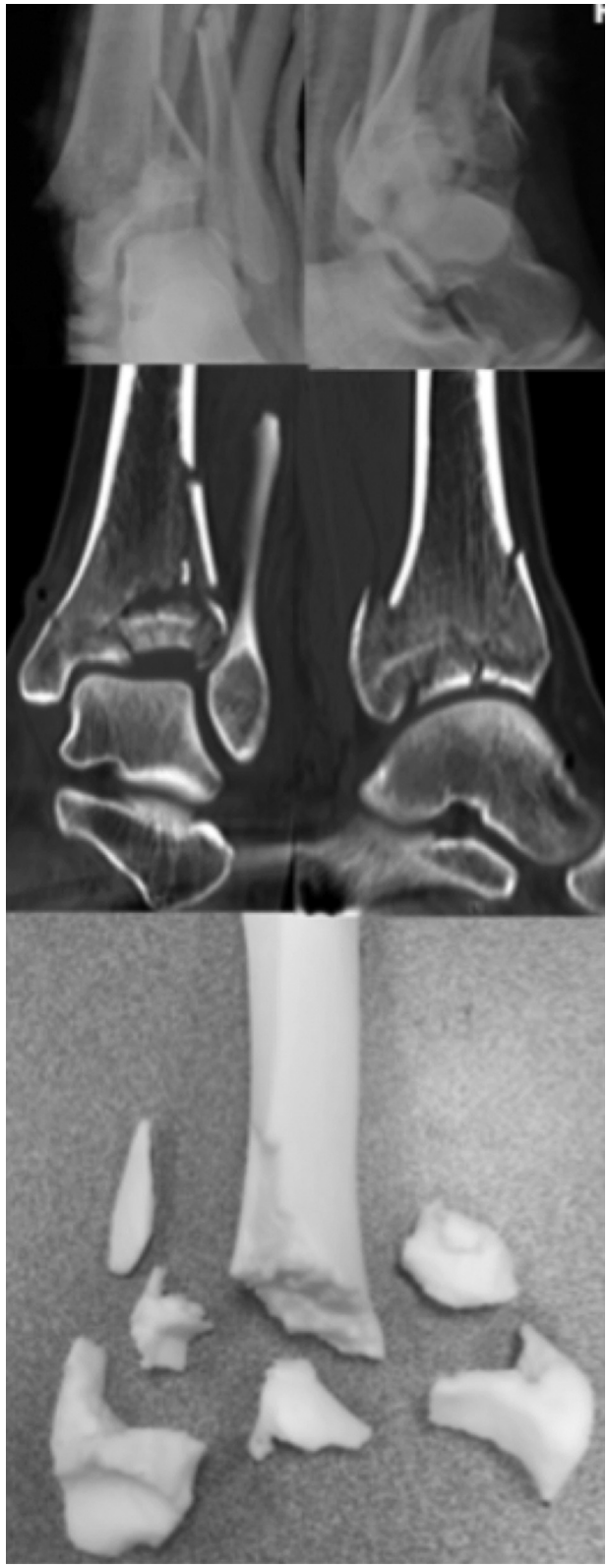


Fig. 4. Radiographs, CT imaging, and 3D model of the complex case.

Study title:
Are 3D Printed Models Useful for Preoperative Planning of Tibia Plafond Fractures?

Subject number:

Date of survey:

What is your current position?
Fellow / Associate Attending / Attending / Senior Attending

How many years of experience do you have managing tibia plafond fractures?

Based on the CT scan for the Basic / Intermediate / Complex case, please provide a pre-operative surgical plan for open reduction and internal fixation of the tibia plafond fracture.
(Please include in your plan the surgical approach, implant selection, reduction techniques etc.)

Having assessed both the CT scan and the 3D model, did the 3D model change your initial pre-operative plan that was made based on the CT scan?
Yes / No
Please elaborate on your answer.

What are the benefits of the synthetic model, if any?
Yes / No
Please elaborate on your answer.

Do you think that the synthetic model coupled with the CT scan is more useful than just the CT scan in pre-operative planning?
Yes / No
Please elaborate on your answer.

How do you rate the usefulness of the synthetic model in pre-operative planning?
0 - 10 (0 = not useful, 10 = extremely useful)

0 1 2 3 4 5 6 7 8 9 10

How do you find the accuracy of the synthetic model in relation to the CT scan?
0 - 10 (0 = not accurate, 10 = extremely accurate)

0 1 2 3 4 5 6 7 8 9 10

How do you rate the ease of use of the 3D model?
0 - 10 (0 = not easy to use, 10 = extremely easy to use)

0 1 2 3 4 5 6 7 8 9 10

Fig. 5. Study questionnaire.

Significance testing was performed using the Kruskal-Wallis test to assess for a difference in all 3 categories (usefulness, accuracy, and ease of use) between the 3 fracture models, with statistical significance defined at 5%.

Results

Six surgeons (4 attending surgeons and 2 fellows) participated in the study. The 6 surgeons have a mean of 3.8 years' (range 2 to 6 years) worth of experience in managing tibial plafond fractures. The mean age of the surgeons is 37 years (range 32 to 39 years old).

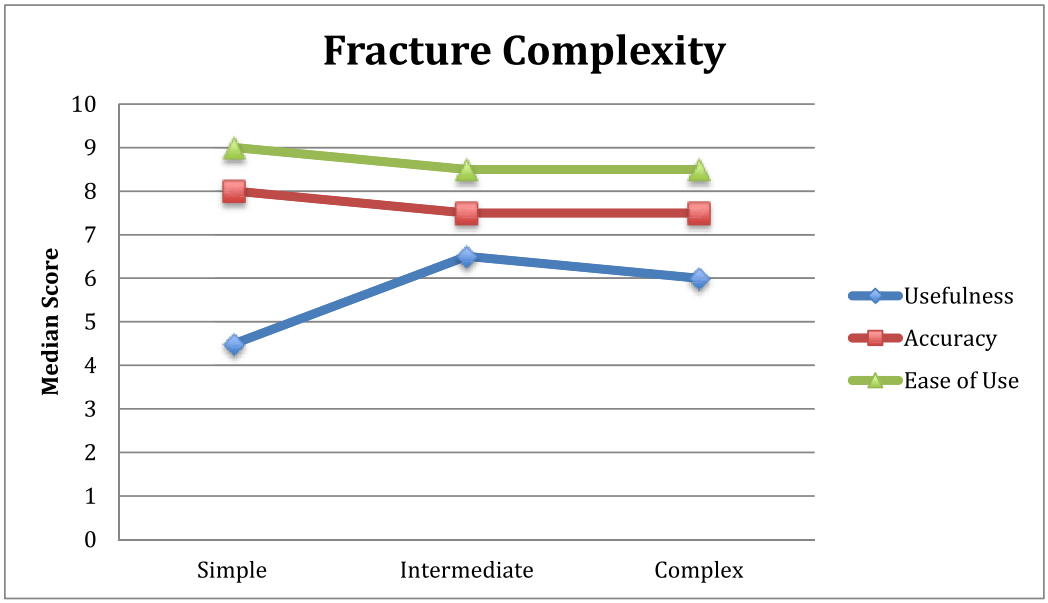
In the simple fracture, none of the surgeons changed their preoperative plans. The median usefulness was graded as 4.5 (range minimum to maximum: 0 to 7), accuracy 8 (4 to 10), and ease of use 9 (7 to 10).

For the intermediate fracture, 2 of the 6 (33.3%) surgeons altered their plans after analysing the fracture model. The median usefulness was 6.5 (2 to 8), accuracy 7.5 (3 to 10), and ease of use 8.5 (7 to 10).

For the complex fracture, only 1 of the 6 (16.7%) surgeons changed his plan. The median usefulness was 6 (1 to 9), accuracy 7.5 (1 to 9), and ease of use 8.5 (0 to 9). These results are summarised in Fig. 6.

Combining the scores for all 3 fractures, the median usefulness of the 3D models was 5.7, accuracy 7.7, and ease of use 8.7.

Using a p value of .05, significance testing using the Kruskal-Wallis test did not reveal a difference in the 3 categories (usefulness, accuracy, and ease of use) between the 3 groups. The significance values are summarised in Fig. 6.



	Simple	Intermediate	Complex	P-value
Usefulness	4.5 (0 to 7)	6.5 (2 to 8)	6 (1 to 9)	0.555
Accuracy	8 (4 to 10)	7.5 (3 to 10)	7.5 (1 to 9)	0.807
Ease of Use	9 (7 to 10)	8.5 (7 to 10)	8.5 (0 to 9)	0.464

Fig. 6. Median scores with minimum to maximum range (usefulness, accuracy, ease of use) and significance values comparing the scores between different fracture complexities.

In the open feedback section, surgeons thought that there were quite a few additional potential advantages of the 3D models aside from being an adjunct in preoperative planning. They noted that the models could be used to contour the appropriate implants preoperatively and as a teaching aid. Four of the 6 surgeons (2 attending surgeons and 2 fellows) answered that the combination of the 3D model and CT scan was more useful than the CT scan alone in their preoperative planning.

Discussion

For traumatology preoperative planning, 3D models are especially useful for complex fractures such as pelvic and intra-articular fractures. The models provide tactile and visual representation, allowing surgeons to plan their surgical approach, implant choice, and reduction techniques (8–11).

Amid the hype surrounding a new technology, there is still the question of whether these models add any meaningful value to currently existing preoperative planning modalities. The gold standard imaging of choice for complex fractures is 3D reconstruction of CT. Another complementary modality is sophisticated preoperative templating software that allow manipulation and templating of fractures in a virtual environment. Implant companies also produce "anatomical" implants designed to fit most patients, reducing the need to contour implants for fracture fixations. These plates are based on anatomical data from population imaging studies but can be skewed by ethnicity and patient size (12,13).

It is in these circumstances that our study set out to assess whether 3D models used alongside CT scans are more useful than CT scans alone in preoperative planning of tibial plafond fractures. We also wanted to explore whether the complexity of the fracture affects the model's usefulness.

For the simple fracture case, none of the surgeons changed their plans. It also had the lowest score for usefulness. This suggests that simple cases can be adequately planned for by using CT scans and that the 3D model does not add any further value to the preoperative planning. The simple model has the highest accuracy because of the easier segmentation of the fragments and scored well in ease of use.

For the intermediate case, 2 surgeons (both attending surgeons) changed their initial plans after analyzing the 3D models. The change in their surgical approach and implant choice was attributed to a better evaluation of the fracture configuration. This ties in with the score for usefulness, which improved to 6.5 (compared to 4.5 for the simple case; $p = .379$). However, there was an absolute although not significant decrease in the accuracy (7.5 compared to 8 for the simple case; $p = .873$) and ease of use (8.5 compared to 9 for the simple case; $p = .749$) scores owing to the more difficult segmentation of the fragments.

For the complex case, the same trend was seen, with increasing usefulness but a drop in the ease of use and accuracy. We attribute these poorer scores to the difficulty in processing the scans and accurate printing of the many fragments in complex impacted fractures. The multiple loose fragments were also not very user-friendly, as the

number of fragments made it more difficult for the surgeon to identify each fragment in relation to the CT scan and how they fit together.

The feedback on the 3D models parallels findings from the current literature (14–16). Two surgeons mentioned that the models would be useful to contour their implants preoperatively. 3D models are already in use to contour implants preoperatively, especially in complex fractures and deformity correction surgeries. This combined with meticulous preoperative planning has the advantage of reducing surgical time and decreasing blood loss and associated morbidities (17,18). However, ABS, the material used in our 3D model, has a relatively low heat resistance and should not be sterilised by steam or autoclave methods. If models are to be used in the operating theatre, they can be sterilised by ethylene oxide or gamma and electron beam radiation (19). If sterilisation can be performed only by steam or autoclave methods, the models can be printed using polyamide material, which has better heat resistance. This is the same material used to produce customised navigation guides in joint arthroplasty, which can tolerate autoclave sterilisation (20).

The 3D models were noted to be a useful teaching aid, allowing junior surgeons to understand the fracture morphology better. A physical model that can be held and felt offers surgeons more direct and intuitive understanding of complex fractures (21,22). The material of the models is also durable enough to be used for fixation with plates and screws based on our preliminary work on an additional model. This facilitates "virtual surgery" for surgeons to practice their fixation (23). To achieve optimal outcomes, anatomical reduction of the articular surface is paramount. Hence, meticulous preoperative planning is crucial to decide on the ideal approach, implant choice, and fixation sequence.

The 3D models as a teaching aid can be extended to the entire operating team to provide guidance on the surgical sequence to improve workflow and teamwork. Thorough understanding of the surgical procedure has been shown to enhance the efficiency and learning experience of the operating team (24,25).

Some of the technical issues that we faced with this study were the segmentation of the relevant fracture segments, especially in comminuted injuries, as well as the time taken to print the 3D models. The timing of the image processing and printing is less relevant in a retrospective study such as ours, but for it to be applicable in a clinical setting, there is a need to streamline the production workflow. The time taken for processing of the images and printing of the models should ideally be within 48 hours. The availability of in-house technical expertise and fast 3D printers are key to achieving this. Given the difficulties we encountered, we highly recommend that the operating surgeon be involved in the image processing stage to determine the segmentation of relevant fracture fragments, especially in comminuted injuries.

The other limitation of our study was the small sample size, as there are only a limited number of surgeons in our institution who manage tibial plafond fractures. This did not allow significantly powerful statistical analysis of the results. We also chose to print only 3 fracture models, taking into consideration the cost and time constraints of fitting in the questionnaire among the surgeons' busy schedules. Moving forward, we intend to print more models of intermediate and complex fractures to better evaluate the efficacy of the models compared to CT scans alone.

The surgeons who participated in this study have a mean of 3.8 years' worth of experience in managing tibial plafond fractures. They ranged from fellows with 2 years' experience to attending surgeons with 6 years' experience. We recognise that the participating surgeons are relatively junior and that senior surgeons with more experience might answer differently.

A thorough knowledge of the soft tissue enveloping the fracture location is vital to decide on the ideal surgical approach. However, our 3D models do not feature these vital structures that include vasculature, nerves, ligaments, muscles, and tendons. Localisation of fracture fragments to which key ligaments and tendons are attached is also useful in guiding reduction and restoration of the joint stability. The selection of surgical approach still ultimately rests on the surgeon's experience and understanding of the approach best suited for the fracture configuration. However, advances in 3D printing are producing hybrid models that incorporate bone and soft-tissue components derived from CT and magnetic resonance imaging scans (26–28). This will prove to be a game-changer in providing models merging the high-fidelity bone profile from CT scans and soft-tissue details from magnetic resonance imaging scans.

In conclusion, 3D-printed fracture models are easy to use and accurate in preoperative planning of tibial plafond fractures. They are more useful in intermediate and complex fractures. The majority of the surgeons in our study believed that a combination of 3D models and CT scan was more useful than CT scan alone. They also quoted other advantages of the 3D models for preoperative plate contouring and as a communication and teaching aid.

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