PREOPERATIVE PLANNING WITH 3D-PRINTED MODELS IN INTERNAL FIXATION FOR COMPLEX TIBIAL PLATEAU FRACTURES: A CASE SERIES

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ABSTRACT

Objectives: To evaluate the feasibility and early outcomes of preoperative planning using 3D-printed models with fragment segmentation and full simulation of internal fixation in Schatzker V/VI tibial plateau fractures. ***Subjects and methods:*** A descriptive case series of 10 patients with S. V/VI tibial plateau fractures treated with open reduction and internal fixation (ORIF) using 3D-printed models for preoperative planning, from January 2025 to April 2026, at the Hospital for Traumatology and Orthopaedics. Patient-specific fracture models were generated from DICOM data using 3D Slicer and Blender, then printed at 1:1 scale on a Creality Ender 5 Pro FDM printer with PLA filament, with 1-mm bridges preserving the initial displacement. Full surgical simulation (reduction – temporary fixation – plate and screw placement) was performed on the printed model. Outcomes assessed: anatomical reduction (Rasmussen's radiological score), knee function (HSS, Rasmussen clinical score), operative time, blood loss, number of fluoroscopic exposures, and adherence to the surgical plan. ***Results:*** Mean age was 48.6 ± 13.2 years; 80% were female. Model preparation was completed within one day. Mean operative time was 117 ± 18 min; mean blood loss 260 ± 69.9 mL; mean fluoroscopic exposures 15.1 ± 4.6; full adherence to the plan was achieved in 80% of cases. The postoperative Rasmussen's radiographic score was 16.4 ± 1.3 (70% excellent, 30% good). At final follow-up, the HSS score was 81.9 ± 5.5 and the Rasmussen clinical score was 24.9 ± 2.9 (90% good – excellent). Mean time to union was 13.4 ± 2.1 weeks. Mean follow-up was 13.6 ± 1.2 months. One case of knee osteoarthritis was recorded. ***Conclusion:*** Preoperative planning using 3D-printed models with fragment segmentation and full simulation of internal fixation is feasible and safe, providing good anatomical and functional outcomes in complex S. V/VI tibial plateau fractures.

Keywords: Tibial plateau fracture, S. V/VI, 3D printing, preoperative planning, internal fixation.

I. INTRODUCTION

Schatzker (S) V and VI tibial plateau fractures are high-energy injuries characterized by multidirectional displacement of multiple fragments, requiring accurate restoration of the articular surface, realignment of the limb axis, and rigid fixation to achieve optimal functional recovery [6,8].

Three-dimensional (3D) printing technology is increasingly applied in preoperative planning, allowing reconstruction of fracture models at 1:1 scale to support visualization, simulation of surgical maneuvers, and selection of fixation devices. Meta-analyses have shown that 3D-assisted surgery may shorten operative time, reduce intraoperative blood loss, decrease the number of fluoroscopic exposures, and shorten healing time compared with conventional surgery [3,9,10].

In Vietnam, several initial studies on the application of 3D printing in tibial plateau fracture surgery have reported encouraging results [1,2,7]. However, these reports were limited either by printing only the assembled fracture as a single block for morphological reference - without a systematic workflow of fragment segmentation, anatomical reduction, temporary fixation, and full simulation of internal fixation [2,7] - or by a small case series [1]. The present study adds to this evolving experience by demonstrating that a complete, fragment-based simulation workflow is feasible within a short preoperative timeframe and can be reliably translated into the actual operation. Such an approach is particularly valuable in any center where the full inventory of implants and instrument sizes cannot be guaranteed in advance, as preoperative simulation allows the surgical team to confirm the precise hardware required before the operation begins.

This study was conducted to evaluate the feasibility and early outcomes of preoperative planning by 3D printing with fragment segmentation and full simulation of internal fixation in patients with S. V/VI tibial plateau fractures.

II. SUBJECTS AND METHODS

2.1. Study design

This was a descriptive case series of 10 patients, conducted from January 2025 to April 2026 at the Hospital for Traumatology and

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Orthopaedics. All patients provided written informed consent.

2.2. Subjects

Inclusion criteria: patients ≥ 18 years of age with closed S.V or VI tibial plateau fractures.

Exclusion criteria: pathological fractures; vascular or neurological injury requiring emergency surgery; previous surgery on the affected tibial plateau; loss to follow-up.

2.3. Preoperative planning protocol with 3D printing

3D model printing: All patients underwent CT scanning with data exported in DICOM format. Images were imported into 3D Slicer (v5.6.2, open-source) for 3D reconstruction; bone segmentation was performed in the Segment Editor module using a threshold of 200–3000 HU, with manual refinement to remove the femur, patella and fibula. The major fracture fragments were identified and segmented separately, then exported in stereolithography (STL) format (one .stl per fragment). The STL files were imported into Blender (v4.2 LTS, open-source) for the design of bridging supports; Blender was preferred for its more robust Boolean mesh operations and better handling of non-manifold geometries at fragment interfaces. With fragments displayed in their original displaced position, 1-mm-diameter cylindrical bridges were created and positioned along the shortest inter-fragmentary distance, avoiding the articular surface and planned screw trajectories, then merged with the bone fragments using the Boolean Union modifier to form a single watertight mesh, which was re-exported as a combined STL file. The combined STL was imported into Ultimaker Cura (v5.7, free open-source slicing software) with the following parameters: layer height 0.20 mm, wall thickness 1.2 mm, infill 15% grid pattern, print speed 60 mm/s, nozzle 210 °C, bed 60 °C, and automatic tree-type supports; the sliced file was exported in G-code (.gcode) format. Physical models were printed at 1:1 scale using a Creality Ender 5 Pro desktop FDM 3D printer with polylactic acid (PLA) filament (1.75 mm) *(Figure 2A, 2B)*.

Surgical simulation: On the printed model, the surgeon carefully observed and assessed each fragment, and planned the operation, including patient positioning, surgical approach, fragment reduction technique, fixation device selection, and the need for bone grafting. Fragments were then sequentially separated, reduced, and temporarily fixed with Kirschner wires. An appropriate plate was selected and contoured if necessary; screw holes were drilled, screw lengths were measured, and screw trajectories were recorded. All technical parameters were documented on the preoperative planning form *(Figure 2C)*.

2.4. Surgery and postoperative follow-up

Surgery was performed under spinal or general anesthesia with a thigh tourniquet. The surgical approach and fixation devices followed the preoperative plan. Adherence was assessed by comparing the actual surgical approach, plate type, number, and length of screws with the plan.

Postoperatively, patients began passive knee motion exercises on day 1, were non-weight bearing for the first 6 weeks, partial weight bearing from week 8, and full weight bearing once radiographic signs of bony union appeared.

2.5. Outcome assessment

Primary outcomes: anatomical reduction (Rasmussen's radiological score-RRS); knee function (Hospital for Special Surgery [HSS] score, Rasmussen clinical score-RCS); and complications. Secondary outcomes: 3D model preparation and simulation time, operative time, blood loss, number of fluoroscopic exposures, and adherence to the preoperative plan. Patients were followed up at 2 weeks, 6 weeks, 3 months, 6 months, and 12 months.

2.6. Statistical analysis

Data were analyzed using SPSS. Continuous variables are presented as mean ± standard deviation; categorical variables are presented as frequencies and percentages.

III. RESULTS

3.1. General characteristics

The study comprised 10 patients with complete 12-month follow-up; general characteristics are summarized in *Table 1*. Mean age was 48.6 ± 13.2 years (range 28–70); 80% were female. All cases resulted from motor vehicle accidents (MVA), with the left knee involved in the majority (70%). Radiographically, 4 cases were S.V and 6 were S.VI; all were classified as 41-C3 according to AO/OTA. By the Luo three-column classification on CT, 9 cases involved three columns and 1 case involved two columns. Overall health status was generally good (ASA I in 4 cases, ASA II in 6 cases). The mean time from injury to surgery was 2.9 ± 1.7 days.

Table 1. General characteristics of the study sample (n = 10)

Case	Age	Sex	Cause	Side	Classification			ASA	Time to surgery (days)	Associated injuries
					Schatzker	AO/OTA	Luo			
1	50	F	MVA	Left	V	C3	3	II	2	ACL: PT; LCL: PT; LM: PHT
2	64	F	MVA	Right	VI	C3	3	II	2	None
3	53	F	MVA	Left	VI	C3	3	II	2	ACL: TSA; LCL: PT
4	53	M	MVA	Left	VI	C3	3	II	2	ACL: TSA; LM: PRT
5	28	F	MVA	Left	V	C3	3	I	2	None
6	32	F	MVA	Right	VI	C3	2	I	2	ACL: TSA; MM: PHT; LM: AHT+PHT
7	38	F	MVA	Left	V	C3	3	I	4	ACL: TSA; LM: PRBA
8	52	F	MVA	Left	VI	C3	3	II	2	MM: BT; LM: AHT
9	46	F	MVA	Left	VI	C3	3	I	4	LM: PHT
10	70	M	MVA	Right	V	C3	3	II	7	ACL: TSA; LM: AHT+PHT

ACL: anterior cruciate ligament; LCL: lateral collateral ligament; MM: medial meniscus; LM: lateral meniscus; TSA: tibial-side avulsion; PT: partial tear; AHT: anterior horn tear; PHT: posterior horn tear; BT: body tear; PRT: posterior root tear; PRBA: posterior root bony avulsion

3.2. 3D printing process and preoperative plan

All 10 patients completed the entire reconstruction – printing – simulation workflow within one day. Mean reconstruction time was 57 ± 11.8 minutes; mean printing time 489.5 ± 45.7 minutes (~8.2 hours); mean simulation time 58 ± 14.6 minutes. The mean planned number of screws was 12.5 ± 1.9 *(Table 2)*.

3.3. Intraoperative results

Mean operative time was 117 ± 18 minutes (90–145); mean blood loss 260 ± 69.9 mL (200–400); mean fluoroscopic exposures 15.1 ± 4.6 (8–22). Full adherence to the plan was achieved in 80% of cases; in two cases, minor modifications were made: retention of a Kirschner wire and adjustment of screw length *(Table 2)*.

Table 2. Preoperative preparation workflow and intraoperative outcomes (n = 10)

Case	Preparation time				Surgical plan				Intraoperative			Adherence
	Recon. (min)	Printing (min)	Simul. (min)	Total (days)	Approach	Plate type	Screws	Bone graft	Op. time (min)	Blood loss (mL)	C-arm	
1	70	480	85	1	AL, M	L, P	13	Yes	125	300	22	Full
2	75	520	70	1	AL, M	L, Re	11	Yes	120	250	20	Partial
3	70	540	75	1	AL, M	L, Re	13	Yes	100	200	17	Full
4	65	430	55	1	AL, MP	L, T-but	15	No	145	400	18	Full
5	55	435	60	1	AL, MP	L, P	15	No	135	350	16	Full
6	50	515	55	1	AL, M	L, M	13	No	110	250	15	Full
7	45	495	45	1	AL, M	L, M	10	No	90	200	8	Full
8	45	550	50	1	AL, M	L, M	10	Yes	110	200	10	Partial
9	45	425	45	1	AL, M	L, M	14	No	100	250	15	Full
10	50	505	40	1	AL, M	L, T-but	11	Yes	135	200	10	Full

AL: anterolateral; M: medial; MP: medial-posteromedial; L: lateral locking plate; P: posteromedial plate; Re: reconstruction plate; T-but: T-buttress plate; min: minutes; Recon.: Reconstruction; Simul.: Simulation; Op.: Operative

3.4. Anatomical recovery outcomes

The postoperative RRS was 16.4 ± 1.3, with 3 excellent and 7 good results. The mean postoperative articular step-off was 1.4 ± 1.3 mm. At the final follow-up, the RRS was 16 ± 1.3, with 2 excellent and 8 good results. Two cases showed secondary depression (3 mm and 2 mm). All patients achieved bony union within 10–16 weeks (mean 13.4 ± 2.1 weeks) *(Table 3)*.

Table 3. Anatomical recovery outcomes (n = 10)

Case	Immediate postoperative					Secondary displacement		Final follow-up		Union (wks)
	Step-off (mm)	Widening (mm)	Angulation (°)	Score	Grade	Depression (mm)	Angulation (°)	Score	Grade	
1	0	0	0	18	Excellent	0	0	18	Excellent	16
2	2	0	0	16	Good	0	0	16	Good	16
3	2	0	0	16	Good	0	0	16	Good	12
4	0	0	4	16	Good	0	0	16	Good	14
5	0	0	0	18	Excellent	3	0	16	Good	10
6	0	0	0	18	Excellent	0	0	18	Excellent	12
7	2	4	0	14	Good	0	0	14	Good	12
8	2	0	0	16	Good	0	0	16	Good	14
9	4	0	0	16	Good	2	0	14	Good	12
10	2	0	0	16	Good	0	0	16	Good	16

3.5. Functional recovery and complications

The mean HSS score increased progressively from 71.3 ± 9.6 at 3 months to 76.6 ± 8.2 at 6 months and reached 81.9 ± 5.5 at the final follow-up: 3 excellent, 6 good, and 1 fair. The RCS was 19.2 ± 4.4 at 3 months, 21.6 ± 4.5 at 6 months, and 24.9 ± 2.9 at the final follow-up: 3 excellent, 6 good, and 1 fair. The mean follow-up duration was 13.6 ± 1.2 months (12–15 months). Only one case (Case 10, a 70-year-old male with S V) developed knee osteoarthritis (OA) *(Table 4)*.

3.6. Illustrative case

Table 4. Functional recovery outcomes (n = 10)

Case	Rasmussen clinical						HSS						Complication	Follow-up (mo)
	3 months		6 months		Final		3 months		6 months		Final			
	Score	Grade	Score	Grade	Score	Grade	Score	Grade	Score	Grade	Score	Grade		
1	17	Fair	20	Good	25	Good	72	Good	75	Good	82	Good	No	15
2	16	Fair	18	Fair	23	Good	63	Fair	68	Fair	83	Good	No	13
3	18	Fair	21	Good	25	Good	65	Fair	72	Good	79	Good	No	12
4	17	Fair	21	Good	24	Good	70	Good	75	Good	83	Good	No	13
5	25	Good	28	Excellent	29	Excellent	78	Good	85	Excellent	86	Excellent	No	14
6	25	Good	27	Excellent	28	Excellent	86	Excellent	87	Excellent	87	Excellent	No	15
7	26	Good	28	Excellent	28	Excellent	87	Excellent	87	Excellent	87	Excellent	No	13
8	17	Fair	19	Good	24	Good	70	Good	77	Good	82	Good	No	12
9	17	Fair	18	Good	24	Good	62	Fair	78	Good	82	Good	No	14
10	14	Fair	16	Fair	19	Fair	60	Fair	62	Fair	68	Fair	OA	15

A 50-year-old woman presented to the emergency department four hours after a motorcycle collision, complaining of left knee pain. Distal neurovascular examination was intact.

Plain radiographs of the left knee demonstrated a S V (AO/OTA 41-C3) tibial plateau fracture. Subsequent CT with 3D reconstruction confirmed a comminuted 3-column fracture (Luo classification) (Figure 1).

Fragment segmentation in dedicated software allowed each principal fragment to be identified and isolated, and the reconstructed fragments were then physically reproduced by 3D printing. Using the printed model, the surgeon disassembled the fragments, performed anatomical reduction, applied temporary fixation, and positioned a lateral locking plate together with a posteromedial locking plate. Drilling and screw insertion were rehearsed on the model, and plate position, screw direction, screw entry points, and screw lengths were documented as the definitive preoperative plan (Figure 2).

The actual operation followed the preoperative plan in full, with an operative time of 125 minutes, blood loss of 300 mL, and 22 fluoroscopic exposures. Postoperative imaging confirmed an anatomical reduction with a RRS of 18 (Excellent) (Figure 3). Bone union was achieved at 16 weeks. At the final 15-month follow-up, the patient had an HSS score of 82 (Good), a RCS of 25 (Good), and the RRS remained 18 (Excellent) (Figure 4). No complications were recorded throughout the follow-up period.

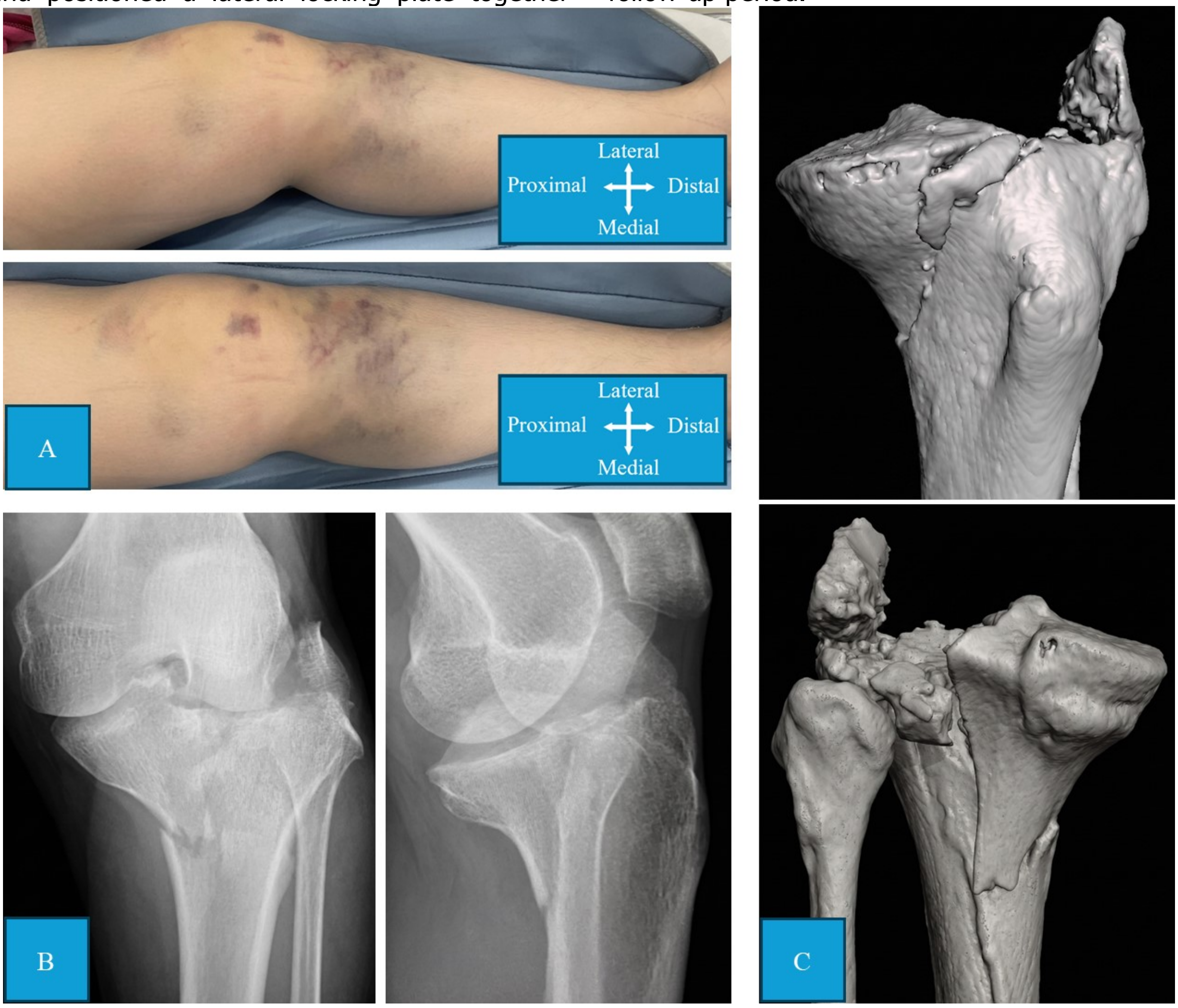

Figure 1. Knee clinical presentation (A), radiographs (B), and 3D CT reconstruction (C) showing a S. V tibial plateau fracture.

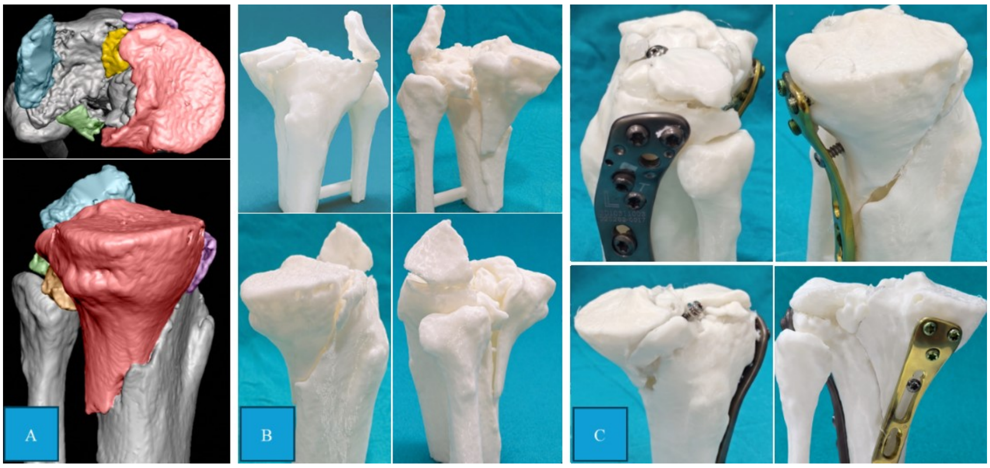

Figure 2. Preoperative planning: segmentation of fracture fragments on 3D software (A), 3D-printed tibial plateau model (B), and the model after anatomical reduction and trial fixation, annotated with plate position, screw length, and screw trajectory (C).

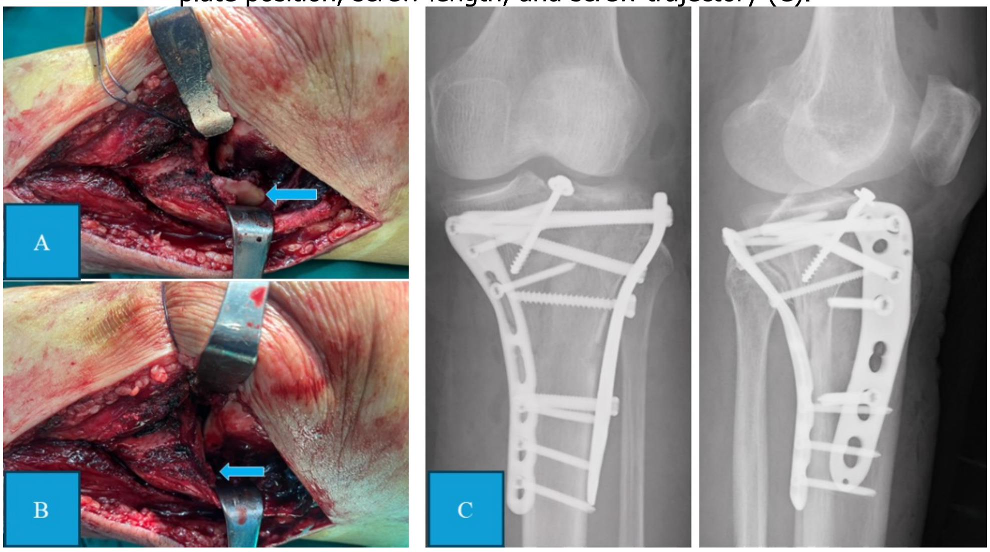

Figure 3. Displaced lateral tibial plateau articular surface before (A) and after reduction (B). Postoperative radiographs (C) show plate and screw placement consistent with the preoperative plan.

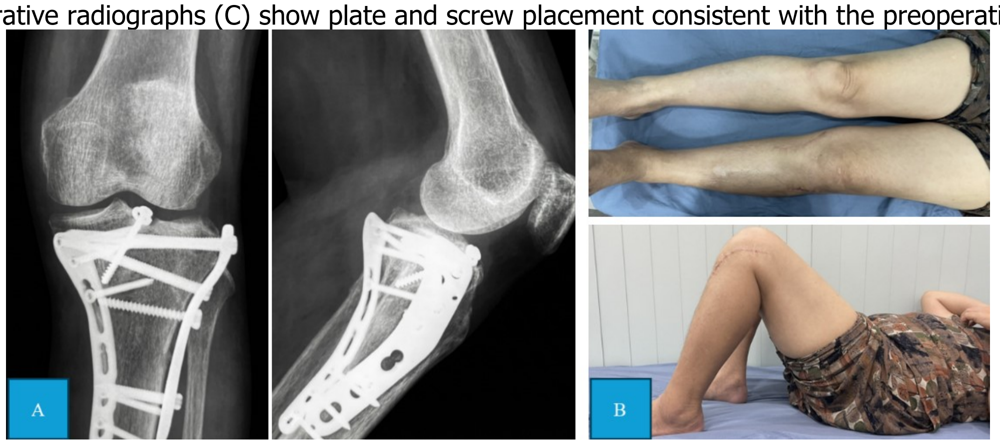

Figure 4. Radiographs at 15 months postoperatively (A) and clinical photographs (B) demonstrating the restoration of anatomical alignment and functional recovery of the knee.

IV. DISCUSSION

This series of 10 patients with S. V/VI tibial plateau fractures treated by ORIF with preoperative planning based on a fragment-segmented 3D-printed model showed that the workflow is feasible, with high adherence (80%) and good anatomical and functional recovery at a mean follow-up of 13.6 months.

In Vietnam, three recent reports have applied 3D printing to tibial plateau surgery using different approaches. Nguyen Trong Sy [2] performed a comparative study in 61 patients (S.I–VI), in which the 3D group printed only the entire fractured block to guide the surgical approach and select the fixation devices. Le Hong Phuc [1] reported only 3 cases with arthroscopic assistance, without detailed description of fragment segmentation. Tran HD et al. [7] applied the three-column concept in 33 patients, achieving an operative time of 115.8 ± 34.2 minutes. The contribution of our report is to demonstrate the feasibility of a fragment-based workflow in a Vietnamese setting, in which the surgeon can physically perform anatomical reduction, temporary fixation, and definitive plate-and-screw placement on the bench prior to operation. This provides a more realistic implant template - plate type, position, screw direction, and length - than is possible with an intact reconstructed model, and is particularly suited to complex bicondylar S.V–VI patterns.

Our study recorded an operative time of 117 ± 18 minutes, comparable to Shen [6] (127.3 ± 8.0), Sy [2] (126.4 ± 40.5), and Tran [7] (115.8 ± 34.2); shorter than Giannetti [12] (148.2 ± 15.9), but longer than Ozturk [5] (89.5 ± 5.9) and Duan [11] (75.3 ± 16). The blood loss of 260 ± 69.9 mL was lower than Sy (341 ± 115.1) and the control group of Ozturk (276 ± 44), but higher than Shen (202.5 ± 36.3), the 3D group of Ozturk (160.5 ± 15.3), and Duan (129.3 ± 25.3), possibly because S. VI accounted for 70% of our sample. The number of fluoroscopic exposures (15.1 ± 4.6) was clearly higher than Shen (6.6 ± 1.1), Duan (6.5 ± 2.1), and the pooled mean from the systematic review by Assink (5.8) [3], likely because we did not use patient-specific drilling guides and were in the early phase of the learning curve.

Regarding articular reduction, our postoperative step-off of 1.4 ± 1.3 mm was lower than both the 3D group (2.9 mm) and the control group (4.0 mm) reported by Assink [4]. The postoperative Rasmussen’s radiographic score of 16.4 ± 1.3 was comparable to Ozturk (15.9 ± 3) and Giannetti (16.1–16.9). In our cohort, only one patient developed mild postoperative malalignment (4°), which remained stable with no further progression at the final follow-up. This compares favorably with the 21.2% malalignment rate (7/33) reported by Tran [7] and the up to 30% suboptimal reduction rate cited in the systematic review by Assink [4], and is consistent with Giannetti [12], who observed no loss of valgus correction at follow-up. Time to union (13.4 ± 2.1 weeks) was longer than Ozturk (9.8 ± 3.3) and Giannetti (12 weeks) but comparable to Duan (13.5 ± 1.4). Tran [7] reported signs of bony union at 12 weeks, comparable to our results.

Functionally, our final HSS of 81.9 ± 5.5 fell within the "good" range, lower than Shen (86.1 ± 7.7) and Duan (90.5 ± 2.2 at 12 months), possibly due to differences in follow-up duration and sample size. The final RCS of 24.9 ± 2.9 was lower than Ozturk (26.8 ± 1), Giannetti (26.9), and Sy (28.4 ± 3.6); however, the samples of Sy and Giannetti included S.I–III, whereas our cohort consisted only of S.V–VI. We observed only 1 of 10 cases with post-traumatic osteoarthritis, no other complications.

Limitations

This study has a small sample size (n = 10) and no control group; therefore, the findings are descriptive and hypothesis-generating. The mean follow-up of 13.6 months is sufficient to assess functional recovery but not to draw conclusions about long-term osteoarthritis, as evidenced by the one case of osteoarthritis observed in this series.

V. CONCLUSION

Preoperative planning with 3D-printed models incorporating fragment segmentation – anatomical reduction – full simulation of internal fixation is feasible and safe in the treatment of S. V/VI tibial plateau fractures. The technique enhances the quality of anatomical reduction and supports favorable functional outcomes. This study provides preliminary data that may serve as a basis for future controlled clinical trials.

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