EFORT open reviews

TRAUMA | 7:4 | 274–286

Double fixation for complex distal femoral fractures

Karl Stoffel[1], Christoph Sommer[2], Mark Lee[3], Tracy Y Zhu[4], Karsten Schwieger[4] and Christopher Finkemeier[5]

[1]Department of Orthopaedics and Traumatology, University Hospital Basel, Basel, Switzerland
[2]Department of Surgery, Kantonsspital Graubuenden, Chur, Switzerland
[3]Department of Orthopaedic Surgery, UC Davis Medical Center, Sacramento, California, USA
[4]AO Innovation Translation Center, AO Foundation, Davos, Switzerland
[5]Sutter Roseville Medical Center, Roseville, California, USA

Correspondence should be addressed to K Stoffel
Email
Karl.Stoffel@usb.ch

- For complex distal femoral fractures, a single lateral locking compression plate or retrograde intramedullary nail may not achieve a stable environment for fracture healing.
- Various types of double fixation constructs have been featured in the current literature. Double-plate construct and nail-and-plate construct are two common double fixation constructs for distal femoral fractures.
- Double fixation constructs have been featured in studies on comminuted distal femoral fractures, distal femoral fracture with medial bone defects, periprosthetic fractures, and distal femoral non-union.
- A number of case series reported a generally high union rate and satisfactory functional outcomes for double fixation of distal femoral fractures.
- In this review, we present the state of the art of double fixation constructs for distal femoral fractures with a focus on double-plate and plate-and-nail constructs.

Keywords
- distal femoral fracture
- double fixation
- double plating
- nail-and-plate construct

EFORT Open Reviews
(2022) **7**, 274–286

Introduction

Distal femoral fractures account for 3–6% of all femoral fractures (1, 2) with less than 10% being comminuted (3). The population sustaining distal femoral fractures is increasingly older with over half occurring in patients over 60 years old (3). Retrograde intramedullary nail (rIMN) and lateral locking compression plate (LCP) are common surgical treatments for distal femoral fractures. Healing difficulties following locking plate are not uncommon. Rates of non-union are up to 19% and rates of implant failure are up to 20% (4). Depending on the degree of comminution, patient characteristics, revision history, and the possible involvement of prostheses, distal femoral fractures can be challenging injuries with relatively high mortality and comorbidity comparable to those of proximal femoral fractures (5, 6, 7).

High-energy injuries frequently result in severe metaphyseal comminution, fractures extended into the articular surface, critical bone defects, or a short distal segment. Eccentric load could lead to varus collapse resulting in hardware failure and non-union (8). Fractures in older patients are often complicated by osteoporotic bone, in which insufficient implant anchorage and poor purchase of screws may obstruct stability (9). For periprosthetic fractures, as the fracture continues around the prosthetic implant, the remaining small bone stock extremely limits the fixation of screws at the condylar area and may result in subsequent instability, which is worsened by the poor bone quality often encountered in these patients (10). Furthermore, limited patient compliance and inability of postoperative partial weight-bearing are factors of growing importance because of the increasing number of older patients with distal femoral fractures. Limiting postoperative weight-bearing could prolong recovery, increase the risk of complications, and negatively impact patients' quality of life (11).

The challenge for the surgeons remains in the balance of providing stable fixation to support physiological loading until union while allowing necessary micromotion for callus formation. In certain complex clinical situations, a single lateral LCP or rIMN may not achieve this balance. These have encouraged the development of double fixation constructs. The goal is to decrease the failure rate by providing stable healing microenvironment that allows early or immediate range of motion and weight-bearing. In this review, we present the state of the art of double fixation constructs for complex distal femoral fractures, for example, high-energy open fractures in a younger population, osteoporotic fractures of the elderly,

www.efortopenreviews.org
https://doi.org/10.1530/EOR-21-0113

or periprosthetic fractures, with a focus on double-plate and plate-and-nail constructs.

Double-plate construct

Rationale and biomechanical studies

The rationale of adding another locking plate is that fixation with a single lateral plate in complex distal femoral fractures could create an unstable environment that contributes to non-union or hardware failure (12). More rigid fixation like double plating provides better stability for a sufficient period of time to allow bone healing in distal femoral fractures with extensive metaphyseal comminution, fractures in osteoporotic bone, and in high-energy or open fractures (13). Biomechanical evidence supporting the use of double plating comes from studies using models of comminuted extraarticular fractures (AO Foundation/Orthopaedic Trauma Association type 33A3) (14, 15, 16), comminuted articular fractures (type 33C) (17, 18, 19), and periprosthetic distal femoral fractures (20). Fontenot *et al.* (17) reported a 70% significant increase in stiffness under axial load when a medial construction plate was added to a single lateral plate in a type 33C fracture model. The torsional stiffness of a double-plate construct was 2.6 times of the single lateral plate and 5.4% higher than that of an rIMN (15). Average load to failure (14, 16) and construct survival rate (17) were significantly higher for double-plate constructs than single lateral plate. Fixation stability is also improved. Double plating showed greater resistance to displacement under axial and torsional load than single lateral plating (14). In a periprosthetic distal femoral fracture model, it reduced the fracture gap motion to 4.3% of the total fracture size under bending and compression load (20). This level of motion is thought to optimize secondary fracture healing in reduced fracture gaps (21).

Double plating for native distal femoral fractures

Most current clinical studies on double plating for distal femoral fractures are retrospective (12, 22, 23, 24, 25, 26, 27, 28) or prospective (29, 30, 31, 32) case series; few are controlled studies comparing double plating with single plating (Table 1) (16, 33, 34, 35, 36). Various surgical approaches have been used (25, 28, 35, 36). Most studies involved the placement of a medial plate in addition to the lateral plate. The study by Ziran *et al.* used an additional anterior plate (26).

Comminuted fractures are the main reason that surgeons opt for double plating in distal femoral fractures (16, 24, 25, 26, 29, 30, 31, 32, 33, 34, 35, 36) (Table 1). Sanders *et al.* (24) reported the first retrospective case series of double plating of comminuted distal femoral fractures. In addition to a non-locking condylar buttress plate on the lateral side, they applied a medial plate with bone graft if intraoperative tests showed motion during flexion and extension of the knee and during application of varus and valgus loads to the knees. They concluded that medial cortical comminution, a short distal condylar fragment, and loss of metaphyseal bone were indications for double plating. Bai *et al.* (33) also used a positive intraoperative varus stress test as an indication for double plating. Swentik *et al.* (25) performed intraoperative assessment of the extent of the soft-tissue injury, the severity of comminution, and the presence of a segmental metaphyseal defect. Dugan *et al.* (27) used double plating for open supracondylar femoral fractures with large bone defect.

Table 2 shows the main results of case series on double plating. Uneventful union rates ranged from 66.7 (26) to 100% (24, 27, 30). Steinberg *et al.* (32) reported the shortest time to fracture healing, where all but two fractures healed radiographically at a mean of 12 weeks and clinically at 11 weeks; however, the study included a few non-comminuted fractures. The mean time to union was the longest (9 months) in the study by Metwaly *et al.* (31), in which only osteoporotic geriatric patients with isolated comminuted fractures (type 33C2/3) were included. There is a less chance of healing of the medial column in osteoporotic bone because of the functional loss of medial cortical buttress (13). Supplementing a medial plate in these patients provides additional stability that prevents varus collapse (13).

Sanders *et al.* (24) developed a scale to evaluate functional outcomes. The scale includes five parameters: knee range of motion (ROM), pain, deformity, walking ability, and return to work. Functional outcome is classified as excellent, good, fair, or poor. Using this scale, Sanders *et al.* (24) reported in their case series that 56% of patients had good and 44% fair function. Knee stiffness was the main reason for fair and poor functional outcomes (30) and was a major problem in a case series of open fractures with critical bone defects treated with double plating (27). Studies using more advanced plating techniques reported better knee motion (25, 29). Three case series reported no complications (23, 24, 27). Five case series reported complication rates at the patient level (25, 28, 29, 30, 32). Khalil and Ayoub (30) used double plating via a modified Oleurud extensile approach for comminuted distal femoral fracture. While 33% of patients experienced delayed union, 50% of patients reported approach-related complications including delayed wound healing, superficial infection, and delayed tibial tuberosity osteotomy healing. Steinberg *et al.* (32) and Imam *et al.* (29) reported complication rates of around 20%. Swentik *et al.* (25) used minimally invasive plate osteosynthesis (MIPO) for medial plating and reported only 2 complications in 11 patients (18.2%).

Table 1 Overview of studies on double plating for distal femoral fractures.

Studies	Design	*n*	Fracture characteristics/indications*	Mean (range) FU duration, months	Surgical details/approach	Medial plate type	Bone graft
Case series							
Sanders *et al.* (24)	Retrospective	9	Müller classification C2.3 (*n* = 4), C3.3 (*n* = 5); 5 open fractures; A medial plate and bone graft were applied if intraoperative tests showed motion during knee flexion and extension and application of varus and valgus loads.	26 (21–34)	Medial plate: extensile approach (*n* = 2), separate medial approach (*n* = 7)	Non-locking condylar buttress plate	Bone graft applied in all cases. Delayed bone graft until the time of wound closure in all open fracture.
Ziran *et al.* (26)	Retrospective	35 (36 fractures)	C2 (*n* = 16), C3 (*n* = 19); 12 open fractures	7.7 (3–44)	Anterior approach Lateral and anterior plate	Reconstruction (*n* = 10) or 3.5mm dynamic compression plate (*n* = 25) for the anterior plate	Allograft and DBM in 28 patients
Khalil & Ayoub (30)	Prospective	12	Müller classification C3 closed fracture	13.7 (11–18)	Modified Olerud extensile approach Lateral and medial plate	Reconstruction plate (*n* = 8), semitubular plate (*n* = 4)	Autogenous iliac bone grafting to fill bony defects
Dugan *et al.* (27)	Retrospective	14 (15 fractures)	C2 (*n* = 7), C3 (*n* = 8): All open fractures due to high trauma; 10 Gustillo Anderson Classification grade 3a, 5 grade 3b; Mean bone defect: 8 cm (range 2.2–11.7 cm)	NR	Thorough open fracture care and lateral plating, followed on average 3.6 months apart, bone grafting and medial plating Medial plate: Extensile anterior approach or medial subvastus approach	Most commonly small fragment combination plates	Autologous bone graft (mostly iliac crest cancellous graft), allograft chip when necessary, and BMP placed over the autogenous graft prior to closure
Holzman *et al.* (12)	Retrospective	22 (23 non-unions)	Distal femoral non-union defined as no clinical and radiographic signs of progression to healing without additional surgical intervention. 3 patients had periprosthetic non-union above a TKA.	18 (6–88.8)	Medial plate: medial parapatellar approach	4.5 mm broad or 4.5 mm narrow LCP	PICBG (16 non-unions); RIA (5 non-unions); BMP (6 non-unions) DBM (2 non-unions)
Steinberg *et al.* (32)	Prospective	32	Native fracture (*n* = 24): A1 (*n* = 1), A2 (*n* = 2), A3 (*n* = 7), C1 (*n* = 4), C2 (*n* = 7), C3 (*n* = 3); Periprosthetic fracture (*n* = 8): 1 Rorabeck-Taylor classification type 1, 7 type 2; 1 open fracture; 2 presented with non-union	12 (8–20)	Lateral and medial approach	A relatively small (8–10 holes) medial plate	NR
Cicek *et al.* (22)	Retrospective	22	Su Type III periprosthetic fracture following primary TKA, stable femoral and tibial components, a T-score of <–3.0 at femoral neck, L4, or L5.	68.6 (39–90)	Arthrotomy using the old TKA midline incision and medial parapatellar approach	NR	Iliac spongious autograft (*n* = 13) and additional cortical,spongious iliac wing autograft (*n* = 5)
Imam *et al.* (29)	Prospective	16	C3 fractures	11.5 (6–24)	Extended anterior approach	Proximal tibial plate (*n* = 10), distal tibial plate (*n* = 5)	Corticocancellous autograft from iliac bone (*n* = 10)
Metwaly & Zakaria (31)	Prospective	23	Isolated, closed, osteoporotic distal femoral fracture in geriatric patients (>60 years). A3 (*n* = 3), C1 (*n* = 2), C2 (*n* = 13), C3 (*n* = 5)	14.1 (12–24)	Either medial or lateral parapatellar approach according to the proximal extent of the lateral condylar fracture.	Locked L-plate or medial distal femoral osteotomy locked plate	4 cases needed autologous bone graft after 6 months of no signs of radiographic union
Swentik *et al.* (25)	Retrospective	11	A3 (*n* = 2), C2 (*n* = 3), C3 (*n* = 6); 10 open fractures (9 Gustilo Anderson type 3A and 1 type 3C); Mean bone loss 8.7 cm. Decision to additional medial plate was based on intraoperative assessment of the extent of soft-tissue injury, severity of comminution, presence of a segmental metaphyseal defect.	NR	MIPO for both plates. Subvastus approach for medial plate.	Small fragment plates and varied in length from 14–18 holes	Staged bone graft in all but 2 cases using the Masquelet technique
Rajasekaran *et al.* (23)	Retrospective	6	Recalcitrant distal femur non-union defined as at least 2 failed surgical attempts. Medial plating plus bone grafting in cases of (1) adequate bone stock, poor fixation/alignment, and medial void > 2 cm; or (2) insufficient bone stock, <65 years old, requiring re-fixation with alignment correction, and medial void > 2 cm.	18.2 (12–33)	NR	NR	Cancellous autograft in all cases

(Continued)

Table 1 Continued.

Studies	Design	*n*	Fracture characteristics/indications*	Mean (range) FU duration, months	Surgical details/approach	Medial plate type	Bone graft
He *et al.* (38)	Prospective	15	Medial OW-DFO for varus malunion after a surgically treated distal femoral fracture	88.8 (48–138)	Medial plate: medial approach Lateral plate: reopening the lateral approach	3.5 mm 6-hole or 8-hole LCP	Autologous bicortical iliac graft ($n = 11$), allograft ($n = 4$)
Beeres *et al.* (28)	Retrospective	11	Peri- and inter-prosthetic fracture ($n = 6$): Su type III periprosthetic supracondylar fracture ($n = 2$), Su type II interprosthetic supracondylar fracture ($n = 2$), A3 fracture with li mited bone stock ($n = 1$), Loss of anchorage distally after initial lateral plate fixation for Su type II supracondylar periprosthetic fracture ($n = 1$); Reoperation ($n = 5$) due to: non-union with infection ($n = 3$), hardware failure ($n = 1$), non-union with varus deformity ($n = 1$)	13	MIPO for both plates	Helical (precontoured on a standard femur saw bone) narrow 4.5 mm large fragment LCP plate	Bone graft used in 4 out of the 5 reopreations
Controlled studies							
Bai *et al.* (33)	Retrospective	SP: $n = 48$ DP: $n = 12$	SP: A ($n = 16$), B ($n = 6$), C1 ($n = 2$), C2 ($n = 4$), C3 ($n = 20$); DP: C1 ($n = 1$), C2 ($n = 2$), C3 ($n = 9$); If the varus stress test turned out positive and rupture of the lateral collateral ligament was excluded, medial plate was set.	SP: 15.2 DP: 8.5	Lateral plate: anterior lateral incision Medial plate: arcuate medial incision	An anatomical plate on the medial side of distal femur or upper limber compressing plate	Bone graft if bone defect >1 cm; No bone grafting: $n = 30$; Autogenous iliac bone graft: $n = 9$; Artificial bone graft: $n = 16$; Combined autogenous iliac and artificial bone graft: $n = 5$
Zhang *et al.* (16)	Randomized study	SP: $n = 16$ (1 lost to FU) DP: $n = 16$ (2 lost to FU)	SP: A2 ($n = 6$), A3 ($n = 9$); DP: A2 ($n = 5$), A3 ($n = 9$)	At 1, 3, 6, and 12 months	Lateral plate: lateral approach Medial plate: medial incision	NR	NR
Zhuang *et al.* (36) #	Retrospective	MI-SP: $n = 24$ MS-SP: $n = 21$ MI-DP: $n = 20$	MI-SP: A2 ($n = 4$), A3 ($n = 8$), C2 ($n = 3$), C3 ($n = 9$); MS-SP: A2 ($n = 9$), A3 ($n = 2$), C1 ($n = 1$), C2 ($n = 8$), C3 ($n = 1$); MI-D P: A2 (n =1), A3 ($n = 4$), C2 ($n = 9$), C3 ($n = 6$)	22.1 (SP: 7.7)	Lateral plate: lateral approach (type 33A) or lateral parapatellar approach (type 33C), MIPO Medial plate: medial mini-invasive incision, MIPO	NR	MI-SP: $n = 4$ (2 iliac bone, 2 TCP block); MS-SP: $n = 4$ (3 iliac bone, 1 TCP block); MI-DP: $n = 6$ (2 iliac bone, 4 TCP block)
Sun *et al.* (35)	Retrospective	SP: $n = 21$ DP: $n = 11$	SP: A2/3 ($n = 13$), C2/3 ($n = 8$), 2 open fractures; DP: A2/3 ($n = 6$), C2/3 ($n = 5$), 1 open fracture No bilateral fracture	12.3 (11–25)	Lateral plate: lateral approach (type 33A) or lateral parapatellar approach (type 33C), MIPO Medial plate: Medial incision, MIPO	PHILOS plate ($n = 6$), reconstruction plate ($n = 5$)	None
Bologna *et al.* (34)	Retrospective	SP: $n = 13$ DP: $n = 8$	SP: C2 ($n = 4$), C3 ($n = 5$), periprosthetic fractures ($n = 4$); DP: C2 ($n = 3$), C3 ($n = 2$), periprosthetic fractures ($n = 3$)	SP: 8 (IQR: 6–15) DP: 13 (IRQ: 11–12)	Lateral plate: lateral approach DP: extensile parapatellar approach	A straight locking plate contoured to the anteromedial surface of distal femur	NR

*Type 33 fractures according to AO Foundation/Orthopaedic Trauma Association Classification unless otherwise indicated. #The study has three groups: medial-instable fractures treated with single plate (MI-SP), medial-instable fracture treated with double plating (MI-DP), and medial-stable fractures treated with single plate (MS-SP). A medial instable distal femoral fracture was defined as a discontinuous and incomplete medial cortex after reduction and a medial stable fracture as a continuous and complete medial cortex.
BMP, bone morphogenetic protein; DMB, demineralized bone matrix; DP, double plating; FU, follow-up; IQR, interquartile range; LCP, locking compression plate; MIPO, minimally invasive plate osteosynthesis; NR, did not report; OW-DFO, open-wedge distal femoral osteotomy;PICBG, autogenous posterior iliac crest bone graft; RIA, autogenous reamer–irrigator–aspirator bone graft; SP, single plating; TCP, beta-tricalcium phosphate; TKA, total knee arthroplasty.

Table 2 Main results of case series of double plating for distal femoral fractures.

Studies	Fracture healing	Knee ROM	Functional outcomes	Deformity	Complications
Sanders *et al.* (24)	All fractures (100%) healed in a mean time of 6.7 months (range 5–9).	Flexion < 90°: *n* = 3 (33.3%); 90–100°: *n* = 5 (55.6%); 100–110°: *n* = 1 (11.1%); 4 patients had flexion contracture of 5°.	5 good, 4 fair*; 1 able to walk without limitation; 8 walked with limitation (3 required a cane).	8 patients had no deformity; 1 had 5° extension contracture; No patients had >2.5 mm shortening.	None
Ziran *et al.* (26)	24/36 (66.7%) fractures healed uneventfully by 16 weeks. 3 non-unions.	Range: 5–100° Extension: 5–35° Flexion: 20–130° 3 patients had small ROM.	NR	NR	2 deaths during hospitalization; 2 infection; 1 arthrofibrosis; 5 manipulation of the knee under anesthesia
Khalil & Ayoub (30)	All fractures (100%) healed radiographically at a mean time of 18.3 weeks (range 12–28). 4 (33.3%) had delayed (>24 weeks) union.	Range: 95–130°	2 excellent, 5 good, 3 fair, 2 poor*. All fair and poor outcomes were due to restricted knee motions.	NR	8 (66.7%) had approach- and/or fracture-related complications: 2 controlled superficial infection, 2 delayed wound healing, 2 delayed (>12 weeks) tibial tuberosity osteotomy healing, 2 restricted knee motion, 3 pain at grafting donor site, 2 manipulation under general anesthesia
Dugan *et al.* (27)	All fractures (100%) healed at a mean time to union of 4 months (range 2–8).	Range: 2–88° Extension: 0–10° Flexion: 40–120°	NR	NR	None
Holzman *et al.* (12)	19/20 patients (20/21 (95.2%) non-unions) available for follow-up attained radiographic union within 12 months.	NR	19/20 patients able to bear partial/full weight on the injured extremity: 13 ambulated without assistive devices, 5 required a cane or walker, 1 required wheelchair ambulator.	NR	6 (30%) patients had complications: 1 persistent non-union, 4 removal of symptomatic hardware, 1 breakdown of posterior iliac crest harvest site
Steinberg *et al.* (32)	All fractures but 2 (93.8%) healed radiographically within a mean of 12 weeks (range 6–12) and clinically within 11 weeks (range 6–17); 1 delayed union.	Extension: 0–20° Flexion: 85–120°	NR	Good axial alignment in all fractures. 1 patient had Valgus of 8°.	5 (15.6%) patients had surgery-related complications: 1 shaft fracture, 2 superficial wound infections, 1 local deep infection after union
Cicek *et al.* (22)	20/22 (90.9%) patients attained radiographic union within a mean (S.D.) of 18.5 (4.3) weeks.	Mean (S.D.): 98.1° (8.2°); Range:70–110°	Mean (S.D.) KSS: 81.8 (7.8) (range 56–90); Mean (S.D.) WOMAC: 78.1 (5.3) (range 62–88); Mean (S.D.) time to pain-free weight-bearing: 4.9 (1.1) (range 4–8) months.	Mean (S.D.) knee valgus angle: 4.9 (1.5°); No genu varum deformity. 2 type 2 notching (Tayside classification), 2 Type 3 notching.	2 revisions with constrained TKA one each due to non-union and reduction loss; 1 superficial infection
Imam *et al.* (29)	Radiographic union at a mean (S.D.) of 6.0 (3.5) (range 3–14) months; 1 patient required re-grafting with a complete union at 14 months.	Mean (S.D.): 114.6° (21.8°) <90°: *n* = 1 (6.25%) 90–120°: *n* = 11 (68.75%) >120°: *n* = 4 (25%)	4 excellent, 7 good, 3 fair, 2 poor*.	No varus or valgus deformity.	4 (25%) patients had complications: 2 infection, 1 secondary procedure, 1 hardware failure
Metwaly & Zakaria (31)	19 (82.6%) uneventful union; 4 (17.3%) required autologous bone graft after 6 months due to non-union; Mean time to full union: 9 months (range 3–12), longer time to union for C3 fracture.	Knee ROM 3–5° less than the contralateral non-fractured side.	NR	NR	6 screw breakage or cutout; 2 superficial wound infection; 1 deep vein thrombosis
Swentik *et al.* (25)	8/10 (80%) (excluding the one with knee amputation) patients had healed fracture without repeated operations; 1 required revision stabilization; 2 with cement spacer in place.	Mean: 106° (in 8 patients) >125°: *n* = 3 (37.5%) 100–124°: *n* = 3 (37.5%) 75–99°: *n* = 1 (12.5%) 50–74°: *n* = 1 (12.5%)	NR	All tibiofemoral angle within acceptable limits. Mean tibiofemoral angle: 6.4° (range 5.7–9.0°) of valgus.	2 (18.2%) patients had major complications: 1 non-union and subsequent implant failure; 1 infection requiring an above the knee amputation
Rajasekaran *et al.* (23)	All 6 (100%) fractures healed (4 at 7 months, 2 at 6 months).	Range: 105–110°	Range of LEFS: 58–71	NR	None

(Continued)

Table 2 Continued.

Studies	Fracture healing	Knee ROM	Functional outcomes	Deformity	Complications
He *et al.* (38)	Mean time to union: 4.1 months (range 2.5–6); 13/21 (61.9%) patients attained radiographic union in 3 months, 8/21 (38.1%) in 3–6 months.	Mean: 3.4–112.55°	All patients initiated full weight-bearing within 3 months; VAS pain score and HSS improved after surgery.	NR	No patient underwent secondary revision or TKA.
Beeres *et al.* (28)	All fractures healed with mean (S.D.) time to radiographic consolidation of 9 (7) months for peri- and interprosthetic fractures and of 6.5 (2) for reoperations.	NR	5 out of 6 patients with peri- and interprosthetic fractures resumed direct postoperative full weight-bearing. 4 out of 5 patients with reoperations achieved full weight-bearing at a mean (S.D.) of 16 (5) weeks.	NR	No patients with peri- and interprosthetic fractures had complication; 1 out of 5 (20%) patients with reoperations developed a fracture-related infection.

*Functional outcomes assessed with a scale developed by Sanders *et al.* (24). The scale includes five parameters: range of motion, pain, deformity, walking ability, and return to work. Functional outcome is classified as excellent, good, fair, or poor.
HSS, Hospital for Special Surgery; KSS, Knee Society Knee Scoring; LEFS, Lower Extremity Functional Scale; NR, did not report; ROM, range of motion; TKA, total knee arthroplasty; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

Table 3 shows the main results of controlled studies. Various types of distal femoral fractures were included (33, 34, 35, 36). Zhang *et al.* (16) reported a randomized, controlled study comparing lateral-and-medial double plating with single lateral plating in 32 patients with type 33A2/3 fractures. Details regarding generation and concealment of randomization sequence as well as blinding were not reported. There were no significant differences between the two groups in time to union, complication rate, knee ROM, and Neer's knee score. The mean time to union was 17 weeks for both groups.

Comparisons between double and single plating are likely biased in retrospective studies as patients undergoing double plating are more likely to have a more complex clinical situation (33). Bai *et al.* (33) found that the double plating group more often required bone grafting, but the two groups had no significant differences in time to bone healing and functional outcomes. Sun *et al.* (35) reported union rates of >90% for both treatments with no significant differences in time to union or knee function. In contrast, Bologna *et al.* (34) found a significantly higher union rate (100% vs 30.8%) and shorter time to union (7 vs 12.5 weeks) for the double plating group. In patients with discontinuous and incomplete medial cortex, double plating resulted in significantly shorter time to bone healing and better knee function than single plating (36).

Double plating for periprosthetic distal femoral fractures

Periprosthetic fractures could pose a significant challenge to stable fixation. Fracture lines are sometimes covered by the prosthesis. The lack of landmarks makes it difficult to obtain accurate anatomical reduction. Blood supply around the knee may be impaired. Local osteoporosis is common. The femoral component of the total knee arthroplasty (TKA) biomechanically weakens the surrounding supracondylar region of the bone (37). In these circumstances, double plating could keep the fracture fragments in place until the calluses are formed and provide sufficient stability. Figure 1 illustrates an 87 years old woman who sustained a left-sided distal femoral fracture with medial comminution after a simple fall. The patient was treated with lateral-and-medial double plating and the fracture was healed with the implants stable *in situ* after 1 year.

Cicek *et al.* (22) reviewed 22 osteoporotic patients with Su Type III periprosthetic distal femoral fractures following primary TKA (Tables 1 and 2). Twenty (91%) patients achieved radiographic union at a mean of 18.5 weeks. Physiological valgus correction was sustained and no varus deformity was detected, indicating that the medial plate provided resistance against varus stress. These resulted in early mobilization and rehabilitation for the patients. The mean (S.D.) time to pain-free weight-bearing was 4.9 (1.1) months. Only two (9.1%) patients required revision due to non-union and reduction loss. A recent study by Beeres *et al.* (28) used MIPO of a helical-shaped plate on the ventromedial side of the femur. The helical plate was precontoured on a standard femur saw bone. In their series of six patients with peri- and interprosthetic distal femoral fracture, five achieved direct postoperative full weight-bearing. Radiographic consolidation was achieved at a mean (S.D.) of 9 (7) months.

Double plating for distal femoral non-union and malunion

Holzman *et al.* (12) hypothesized that a single lateral plate created an unstable microenvironment that contributed to non-union. They reviewed 23 non-unions managed with additional medial locking plate and autogenous bone graft with the lateral plate *in situ* or in cases of septic non-union or lateral plate failure, placement of a new lateral plate (Table 1). Their treatment algorithm achieved a radiographic union rate of 95.2% within 12 months

Table 3 Main results of controlled studies of double plating for distal femoral fractures.

Studies	Baseline characteristics	Surgery details	Bone healing	Functional outcomes	Complications
Bai *et al.* (33)	No difference in age, gender, no. of extra location of fractures; Significantly more traffic accidents (83.3% vs 16.7%), type C fracture (100% vs 54.2%), open fracture (91.7% vs 52%) in DP group.	No difference in surgery duration and blood loss. Significantly more bone grafting in DP group (91.7% vs 40.4%).	No difference in rate of bony union (SP vs DP: 97.9% vs 100%) and time to healing (SP vs DP: 14.3 vs 18 months).	No difference in Kolmert's standard of excellent and good rates (SP vs DP: 81.3% vs 75%).	1 fixation failure and 1 non-union in SP group. None in DP group.
Zhang *et al.* (16)	No difference in age, sex, and fracture type.	No difference in blood loss. Significantly longer surgery duration for DP group (104.29 vs 88 min).	Mean time to union of 17 weeks for both groups.	No difference in pain VAS score, ROM, and Neer knee score at 1, 3, 6, and 12 months.	No difference in complication rate; In SP group, 1 death due to pneumonia at 6 months, 1 superficial infection, and 1 pain and implant prominence after healing; In DP group, 1 deep vein thrombosis and 1 pain and implant prominence after healing.
Zhuang *et al.* (36)*	NR	No difference in surgery duration and blood loss.	All fractures but 2 healed within 6 months with no difference in healing rate (MI-DP vs MS-SP vs MI-SP: 100% vs 100% vs 91.7%). Significantly shorter time to healing for MI-DP and MS-SP group (MI-DP vs MS-SP vs MI-SP: 15.1 ± 2.3 vs 14.9 ± 2.2 vs 21 ± 13.9 weeks).	No difference in knee ROM; Significantly greater KSS for MI-DP and MS-SP group (MI-DP vs MS-SP vs MI-SP: 88.7 ± 9.4 vs 89.1 ± 7.3 vs 82.9 ± 7.5).	In MI-SP group, 1 each patient had delayed union, non-union, and knee varus; In MI-DP group, 1 patient had deep infection; In MS-SP group, 1 patient had knee varus.
Sun *et al.* (35)	NR	No difference in blood loss; Significantly longer surgery duration for DP group (129.5 vs 98.8 min).	No difference in percentage of bone healing (DP vs SP: 100% vs 91%); No difference in time to bone healing (5.39 ± 0.69 vs 5.86 ± 0.59 months).	No difference in HSS score of excellent or good results (DP vs SP: 90% vs 85.7%).	2 non-unions in SP group; 1 superficial wound infection in DP group.
Bologna *et al.* (34)	NR	NR	Significant higher percentage of union in DP group (100% vs 30.8%); Significantly shorter time to union in DP group (7 vs 12.5 weeks).	No difference in time to full weight-bearing. Significantly greater knee ROM in SP group (100° (92.5–115°) vs 90° (70–90°)).	No difference in revision ORIF (DP vs SP, 0 vs 4, $P = 0.13$); In SP group, 6 non-union, 3 delayed union, 1 infection; In DP group, 2 significant knee stiffness, 2 mild anterolateral heterotopic ossification.

(Table 2). Nineteen (95%) patients with radiographic union resumed full or partial weight-bearing. Six (30%) patients had complications including one persistent non-union, four symptomatic hardware, and one superficial wound breakdown. In contrast, Rajasekaran *et al.* (23) acknowledged the multifactorial nature of distal femoral non-union, and their stepwise treatment algorithm was based on four parameters: distal femoral bone stock, fracture alignment, medial void, and stability of fixation. Following revision fixation and alignment correction, an additional medial plate combined with bone graft to mechanically restore medial continuity was only indicated when medial defects were >2 cm. Of the 62 patients treated with this algorithm, six underwent additional medial plating and bone graft. Two patients achieved union in 6 months and four in 7 months. Knee ROM ranged from 105° to 110°. Beeres *et al.* (28) applied MIPO of an additional helical-shaped plate on the ventromedial side of the femur in five patients requiring reoperation due to non-union and hardware failure with large bone defects. This technique allowed immediate postoperative partial weight-bearing. Four patients achieved full weight-bearing after a mean (s.d.) of 16 (5) weeks.

The prospective study by He *et al.* recruited 15 patients with distal femoral varus malunion after surgery for distal femoral fractures (38). Correction for varus deformity was through medial open-wedge distal femoral osteotomy. A 6- or 8-hole LCP was placed medially to buttress the open

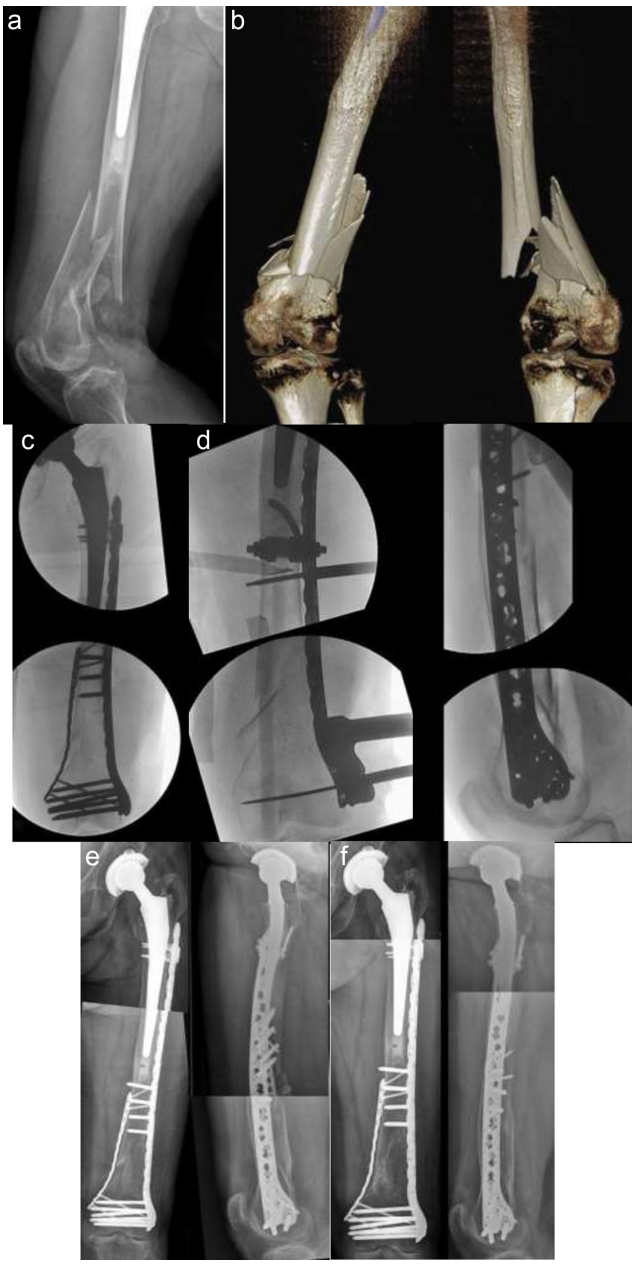

Figure 1

Conventional X-rays of an 87-year-old woman (A, only in one plane due to technical difficulties). The CT scans show a distal multifragmentary periprosthetic extraarticular femoral fracture with medial comminution in the presence of severe osteoporosis with thin cortical bone and rarefied trabeculae. Due to the fracture pattern, poor bone quality, obesity, and impaired compliance of the patient, it was decided to use a double plating technique with a lateral 4.5 mm VA-LCP Condylar Plate and a medial small fragment plate, allowing to insert many screws in the distal articular part from both sides (B). After application of an external fixator anteriorly, a 4.5 mm VA-LCP Condylar Plate was percutaneously applied and preliminary fixed with the nominal screw parallel to the joint. Proximal the plate was compressed to the bone using the Whirly Bird device (C). The long plate was proximally fixed to the shaft with a Locking Attachment Plate. Then, a second straight 3.5 LCP was precontoured (bending, twisting) and applied medially through a minimally invasive approach distally. The two screws proximally were inserted percutaneously (D). Postoperative X-rays demonstrate a well-reduced and aligned fracture, stabilized with two plates bridging the metaphyseal comminution. The lateral curved plate is in the anteroposterior and lateral views well centered and all screws in the distal plate are oriented at or close to nominal angle. Given the patient's age and comorbidities (e.g. dementia), she was allowed to full weight-bear using a walker (E). After 1 year, the fracture is healed with the implants stable *in situ*. She is back to walking as before the injury (F).

osteotomy gap, followed by placing an additional 10-hole or longer LCP or less invasive stabilization system laterally. The lateral plate acted as a fixed-angle device to counteract most of the instability created by the osteotomy. The improved stability allowed scheduled weight-bearing between 8 and 12 weeks and prevented loss of correction. In all patients, varus and flexion malalignment and limb discrepancy were adequately corrected. Bone healing was achieved within a mean of 4.1 months. Patients also achieved good functional outcomes with mean knee ROM of 3.4–112.55° at 24 months. No fixational failure or secondary surgery was recorded.

Concerns of double plating

Despite significant heterogeneity of patient and fracture characteristics as well as surgical techniques employed, most studies concluded that in certain complex clinical situations, double plating increased fixation construct rigidity, facilitated graft impaction, prevented varus collapse, and promoted union without loss of reduction. The major concerns of double plating are further soft-tissue stripping and compromised periosteal blood supply, which may induce a higher risk of infection (39). A recent cadaveric study, however, showed that additional medial plating did not lead to marked devascularization of the distal femur (40). Most vascular injuries occurred with lateral plating alone. An additional medial plate only incurred an additional 4.2% decrease in arterial contribution to the 21.2% decrease with a single lateral plate. The amount of soft-tissue stripping can be limited with more minimally invasive procedures to avoid excessive scar formation and knee stiffness (25, 28). A cadaveric study has demonstrated the safety and feasibility of MIPO on the medial side of the femur (41). There were no disruptions of superficial or deep femoral arteries when operated at the distal 60% of the femur length, measured from the tip of the greater trochanter to the lateral joint line of the knee. A few studies have used MIPO for medial plating and report no significantly elevated risks of vascular injuries (25, 35, 36).

Another major concern of double plating is that too much construct stiffness could result in delayed healing or non-union. Construct stiffness can be modified by selecting the appropriate plate size to balance the fixation. Small fragment plates are most commonly used as a medial plate. It is a common practice to use double plating at the proximal tibia with small fragment plates. Considering the load transfer in the knee joint between proximal tibia and distal femur, such a plating technique could also be enough at the distal femur; however, this remains a postulation and requires further studies.

Nail-and-plate construct

Rationale and biomechanical studies

An alternative to double plating is the nail-and-plate construct. It involves the placement of an rIMN and a supplemental lateral plate (42, 43). Although there is no consensus on the sequence of the procedure, in all the current studies, the rIMN was inserted first, followed by the placement of the lateral plate. Liporace and Yoon (42) hypothesized that placing an rIMN first moves the weight-bearing axis of the femur medially and closer to the anatomical axis of the femur. The lateral locking plate provides added stability. By linking the nail and the plate distally while spanning the entire length of the femur, forces are more smoothly transferred between the bone and the implant. This construct offers a balance of stability and micromotion that maximizes the probability of healing and early return to function. Figure 2 illustrates an 84-year-old woman who sustained a left periprosthetic distal femoral fracture and was successfully managed with a nail-and-plate construct.

The nail-and-plate construct was more resistant to displacement than lateral plate or rIMN alone under torsional and axial load in a type 33A3 femoral fracture model (44). In a type 33C femoral fracture model, the nail-and-plate had the highest number of cycles to failure, which was significantly better than the single lateral plate, despite not being superior than the double-plate construct (17).

Clinical studies of nail-and-plate construct

Several case series have used the nail-and-plate construct in different clinical situations and reported overall high union rates (42, 45, 46, 47, 48). Liporace and Yoon (42) used the nail-and-plate construct for primary fracture fixation

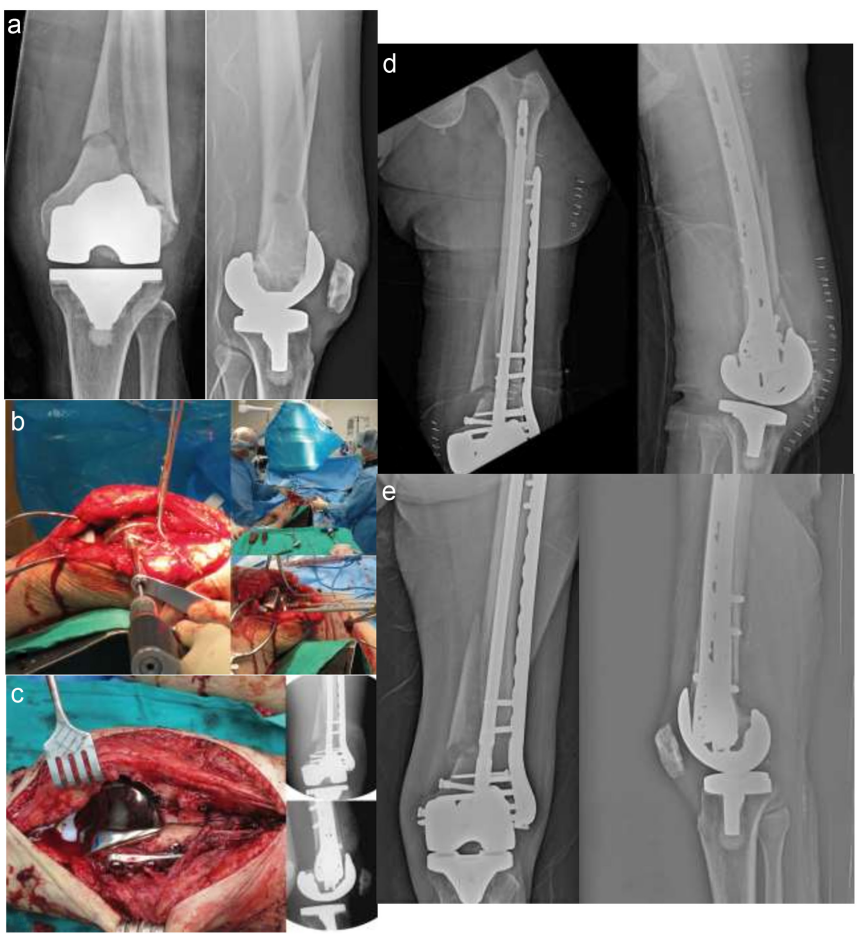

Figure 2
X-rays of the injury. The medial column is deficient because of a butterfly bone fragment. There is a low lateral column 'escape' fracture line that is challenging for fixation with a lateral plate (A). After restoration of coronal and sagittal plane alignment, a VA-LCP condylar plate was applied to hold the alignment and axis. Screws were placed out of the path of the nail. Unicortical screws were placed in the diaphysis (B). Placement of a retrograde femoral intramedullary nail. Medial cortical substitution is covered by the nail (C). Postoperative imaging. Immediately after surgery the patient could apply weight-bearing as tolerated (D). Follow-up X-rays at 4 months after surgery (D).

in six patients with native and nine with periprosthetic distal femoral fractures. Except for one patient who died of unrelated comorbidity, all fractures went on to heal. Patients were able to immediate bear weight and all remained ambulatory, mostly with an assistive device. There was no hardware failure. Two patients experienced complications. One patient with native fracture underwent subsequent ipsilateral TKA unrelated to the fixation construct and one had a superficial wound infection that resolved with oral antibiotics.

Knabur *et al.* (48) published a technique guide and case series on nail-and-plate construct for periprosthetic fractures. Patients were either osteopenic, overweight/obese, or both. Fractures were treated with a statically locked rIMN and a lateral flare-to-flare locking plate without augmentation with autograft or allograft. Patients were weight-bearing restricted for approximately 4 weeks and then progressed to partial weight-bearing. After a mean follow-up of 20.6 months, all patients had radiographic union and were able to ambulate independently or with an assistive device. Hussain *et al.* (47) applied the nail-and-plate construct to nine patients with non-comminuted interprosthetic distal femoral fractures between a total hip arthroplasty and TKA. Immediate weight-bearing with the use of a walker was initiated after the surgery. All fractures healed at a mean of 20 weeks. Varus/valgus angulation was within physiological limits. Five (56%) patients maintained their pre-injury level of independence and four (44%) lost one level of independence. The procedure was deemed safe with only one postoperative deep vein thrombosis.

Several case series have demonstrated the effectiveness of supplementing a lateral plate to an *in situ* rIMN for treating femoral non-union (45, 49, 50, 51, 52, 53, 54). The number of femoral non-unions from these studies ranged from 5 (54) to 25 (52). All studies reported a 100% union rate with mean time to union ranging from 3.9 (45) to 7.3 months (54). The largest series by Birjandinejad *et al.* (52) reviewed 38 patients including 25 femoral non-unions and 13 tibial non-unions. All femoral non-unions and all but two tibial non-unions achieved union at a mean of 4.78 months. The shortest mean time to union (3.9 months) was reported by a recent case series of ten patients with distal femoral non-union treated with nail-and-plate construct and autogenous bone grafting (45). In this study, eight (80%) patients could tolerate weight-bearing immediately after the repair; the remaining two began weight-bearing at 8 and 12 weeks, respectively. There was no loss of alignment. The only complication was wound infection that was recorded in two patients.

Benefits and limitations of nail-and-plate construct

The small number of studies showed that nail-and-plate construct could be a viable option for native and periprosthetic distal femoral fractures as well as distal femoral non-union. Compared with double plating, nail-and-plate construct may cause less soft-tissue insult and blood loss, which may lower the risk of infection. The construct allows smoother load transfer at the fracture site and in some cases, permits immediate postoperative weight-bearing. This may have a significant positive effect on patients' quality of life. Because bone quality is usually diminished due to the presence of a prosthesis component, nail-and-plate construct could be particularly advantageous for periprosthetic fracture. A potential advantage of the nail-and-plate construct over double plating is that, with the presence of the nail, the lateral plate could be removed before complete healing if necessary. Nonetheless, in cases of articular comminution, double plating still offers advantages over nail-and-plate construct. Furthermore, it may not be possible to insert an rIMN in the presence of a knee prosthesis. The plate-and-nail construct is only feasible when the knee component has an open box and an rIMN must fit the dimensions of the intercondylar notch of the knee component *in situ*.

The potential benefit of linking the nail to the plate via interlocking screws is being debated and requires further study. The hypothesis is that there is more equal load distribution between the nail and the plate if there is linkage between them, which could be beneficial for fracture healing and avoid premature construct failure of one of the devices.

Other double fixation constructs

Other variations of double fixation constructs have been used in a few case series. Bergin *et al.* (8) used an intraosseous plate in additional to a lateral extraosseous plate in ten patients with complex fractures with extensive bone loss and non-union reconstruction, seven of which were in the distal femur. After the intraosseous plate was centered on the fracture, defect, or non-union, the extraosseous plate was position and stabilized. The intraosseous plate was compressed against the medial cortex to provide additional support to the medial column. The two plates were interlocked, and their distance determined the ultimate strength of the construct. The technique could be technically demanding and time-consuming but offered satisfactory outcomes. Eight (80%) fractures healed without further intervention and two (20%) healed after one additional surgery each. Spitler *et al.* (55) used an intramedullary rod interlocked with a lateral locking plate to compensate for the structural defect of the medial cortex at the femur. The construct could be applied with either a plate-first or rod-first technique. In their series, seven of eight patients with acute fracture and all eight patients with non-union healed without an unplanned reoperation. Carnavos *et al.* (56) used a

combination of rIMN and compression condylar bolt for intraarticular distal femoral fractures. The compression bolt was inserted prior to the rIMN to secure the intercondylar fracture. All fractures healed uneventfully at a median of 15 weeks. Partial weight-bearing was initiated at a mean of 6.35 weeks postoperatively and full weight-bearing at 14.6 weeks.

Conclusions and outlook

There is a growing need for double fixation constructs for complex distal femoral fractures and non-union in which a lateral plate or an rIMN alone is insufficient to maintain the stability necessary for healing. This trend is driven by the increasing aging population and high activity demands. High load-bearing capacity of the double fixation construct provides a stable microenvironment that promotes healing and allows early or immediate weight-bearing. This is particularly appealing for patients who cannot follow partial weight-bearing protocol. Various types of double fixation constructs presented in the current literature so far have demonstrated good clinical outcomes such as high union rate and satisfactory function. The concept of double fixation is promising but needs further investigation.

Most of the current studies are case series and of retrospective design. The lack of comparators, that is alternative treatments, makes it difficult to determine the type of fracture or non-union that would benefit from a double fixation construct and to determine the suitable construct that meets the needs of the clinical situation. Future prospective controlled studies should include at-risk patients and compare various available treatments. They should also standardize or even compare the surgical approach and the use of adjunct treatments that would potentially influence the outcomes, notably the use of bone graft.

A factor that must be considered when selecting a double fixation construct and device dimensions is the risk of peri-implant fractures due to potential stress risers adjacent to the fixation construct. Every double fixation construct needs to be 'adequately' balanced to induce bone healing. What 'adequately' means in this context requires further clarifications and consensus from the community. Since the load is transferred via two devices, the dimensions of these devices and in case of a nail-and-plate construct, the presence of a linkage between them determine how much load is transferred by which device and what the failure modes are. Future developments also involve implants that are anatomically shaped and appropriate for double fixation constructs, such as a dedicated distal medial femoral plate for double plating, a distal medial plate as a single plate, or a dedicated nail-and-plate construct for distal femoral fractures.

ICMJE Conflict of Interest Statement

Christoph Sommer declares no conflict of interest. Karl Stoffel declared financial educational support from Mathys Medical and Corin GSA for the presented work and consultancy fees from DePuy Syntes, Mathys Medical, and Gorin GSA outside of the presented work; the financial educational support and the consultancy fees were received by Karl Stoffel's institute (University Hospital Basel) for his efforts. Mark Lee reported personal fees from DePuy Synthes and Osteocentric outside the submitted work. Christopher Finkemeier reported personal fees from DePuy Synthes outside the submitted work, and he is the Chairman of the AOTC Intramedullary Nailing Expert Group who is involved with the development and evaluation of new nailing implants and instruments manufactured by DePuy Synthes. Tracy Y Zhu and Karsten Schwieger are employees of AO Innovation Translation Center, AO Foundation, which has partly funded this work.

Funding Statement

This work was partly funded by the AO Technical Commission, AO Innovation Translation Center, AO Foundation, Davos, Switzerland.

References

1. Martinet O, Cordey J, Harder Y, Maier A, Buhler M & Barraud GE. The epidemiology of fractures of the distal femur. *Injury* 2000 **31** (Supplement 3) C62–C63. (https://doi.org/10.1016/s0020-1383(00)80034-0)

2. Court-Brown CM & Caesar B. Epidemiology of adult fractures: a review. *Injury* 2006 **37** 691–697. (https://doi.org/10.1016/j.injury.2006.04.130)

3. Elsoe R, Ceccotti AA & Larsen P. Population-based epidemiology and incidence of distal femur fractures. *International Orthopaedics* 2018 **42** 191–196. (https://doi.org/10.1007/s00264-017-3665-1)

4. Henderson CE, Kuhl LL, Fitzpatrick DC & Marsh JL. Locking plates for distal femur fractures: is there a problem with fracture healing? *Journal of Orthopaedic Trauma* 2011 **25** (Supplement 1) S8–S14. (https://doi.org/10.1097/BOT.0b013e3182070127)

5. Jordan RW, Chahal GS, Davies M & Srinivas K. A comparison of mortality following distal femoral fractures and hip fractures in an elderly population. *Advances in Orthopedic Surgery* 2014 **2014** 1–4. (https://doi.org/10.1155/2014/873785):873785.

6. Smith JR, Halliday R, Aquilina AL, Morrison RJ, Yip GC, McArthur J, Hull P, Gray A, Kelly MB & Collaborative – Orthopaedic Trauma Society (OTS). Distal femoral fractures: the need to review the standard of care. *Injury* 2015 **46** 1084–1088. (https://doi.org/10.1016/j.injury.2015.02.016)

7. Streubel PN, Ricci WM, Wong A & Gardner MJ. Mortality after distal femur fractures in elderly patients. *Clinical Orthopaedics and Related Research* 2011 **469** 1188–1196. (https://doi.org/10.1007/s11999-010-1530-2)

8. Bergin PF, Weber TG, Gerow DE, Spitler CA, Graves ML & Russell GV. Intraosseous plating for the management of cortical defects. *Journal of Orthopaedic Trauma* 2018 **32** (Supplement 1) S12–S17. (https://doi.org/10.1097/BOT.0000000000001095)

9. Wahnert D, Hoffmeier K, Frober R, Hofmann GO & Muckley T. Distal femur fractures of the elderly – different treatment options in a biomechanical comparison. *Injury* 2011 **42** 655–659. (https://doi.org/10.1016/j.injury.2010.09.009)

10. Streubel PN, Gardner MJ, Morshed S, Collinge CA, Gallagher B & Ricci WM. Are extreme distal periprosthetic supracondylar fractures of the femur too distal to fix using a lateral locked plate? *Journal of Bone and Joint Surgery: British Volume* 2010 **92** 527–534. (https://doi.org/10.1302/0301-620X.92B3.22996)

11. Schottel PC, O'Connor DP & Brinker MR. Time trade-off as a measure of health-related quality of life: long bone nonunions have a devastating impact. *Journal of Bone and Joint Surgery: American Volume* 2015 **97** 1406–1410. (https://doi.org/10.2106/JBJS.N.01090)

12. Holzman MA, Hanus BD, Munz JW, O'Connor DP & Brinker MR. Addition of a medial locking plate to an in situ lateral locking plate results in healing of distal femoral nonunions. *Clinical Orthopaedics and Related Research* 2016 **474** 1498–1505. (https://doi.org/10.1007/s11999-016-4709-3)

13. Sain A, Sharma V, Farooque K, V M & Pattabiraman K. Dual plating of the distal femur: indications and surgical techniques. *Cureus* 2019 **11** e6483. (https://doi.org/10.7759/cureus.6483)

14. Park KH, Oh CW, Park IH, Kim JW, Lee JH & Kim HJ. Additional fixation of medial plate over the unstable lateral locked plating of distal femur fractures: a biomechanical study. *Injury* 2019 **50** 1593–1598. (https://doi.org/10.1016/j.injury.2019.06.032)

15. Wright DJ, DeSanto DJ, McGarry MH, Lee TQ & Scolaro JA. Supplemental fixation of supracondylar distal femur fractures: a biomechanical comparison of dual-plate and plate-nail constructs. *Journal of Orthopaedic Trauma* 2020 **34** 434–440. (https://doi.org/10.1097/BOT.0000000000001749)

16. Zhang J, Wei Y, Yin W, Shen Y & Cao S. Biomechanical and clinical comparison of single lateral plate and double plating of comminuted supracondylar femoral fractures. *Acta Orthopaedica Belgica* 2018 **84** 141–148.

17. Fontenot PB, Diaz M, Stoops K, Barrick B, Santoni B & Mir H. Supplementation of lateral locked plating for distal femur fractures: a biomechanical study. *Journal of Orthopaedic Trauma* 2019 **33** 642–648. (https://doi.org/10.1097/BOT.0000000000001591)

18. Jazrawi LM, Kummer FJ, Simon JA, Bai B, Hunt SA, Egol KA & Koval KJ. New technique for treatment of unstable distal femur fractures by locked double-plating: case report and biomechanical evaluation. *Journal of Trauma* 2000 **48** 87–92. (https://doi.org/10.1097/00005373-200001000-00015)

19. Zhang W, Li J, Zhang H, Wang M, Li L, Zhou J, Guo H, Li Y & Tang P. Biomechanical assessment of single LISS versus double-plate osteosynthesis in the AO type 33-C2 fractures: a finite element analysis. *Injury* 2018 **49** 2142–2146. (https://doi.org/10.1016/j.injury.2018.10.011)

20. Muizelaar A, Winemaker MJ, Quenneville CE & Wohl GR. Preliminary testing of a novel bilateral plating technique for treating periprosthetic fractures of the distal femur. *Clinical Biomechanics* 2015 **30** 921–926. (https://doi.org/10.1016/j.clinbiomech.2015.07.008)

21. Egol KA, Kubiak EN, Fulkerson E, Kummer FJ & Koval KJ. Biomechanics of locked plates and screws. *Journal of Orthopaedic Trauma* 2004 **18** 488–493. (https://doi.org/10.1097/00005131-200409000-00003)

22. Cicek H, Tuhanioglu Ü, Ogur HU, Seyfettinoglu F & Bozkurt M. An alternative treatment for osteoporotic Su Type III periprosthetic supracondylar femur fractures: double locking plate fixation. *Acta Orthopaedica et Traumatologica Turcica* 2018 **52** 92–96. (https://doi.org/10.1016/j.aott.2017.09.010)

23. Rajasekaran RB, Jayaramaraju D, Palanisami DR, Agraharam D, Perumal R, Kamal A & Rajasekaran S. A surgical algorithm for the management of recalcitrant distal femur nonunions based on distal femoral bone stock, fracture alignment, medial void, and stability of fixation. *Archives of Orthopaedic and Trauma Surgery* 2019 **139** 1057–1068. (https://doi.org/10.1007/s00402-019-03172-0)

24. Sanders R, Swiontkowski M, Rosen H & Helfet D. Double-plating of comminuted, unstable fractures of the distal part of the femur. *Journal of Bone and Joint Surgery: American Volume* 1991 **73** 341–346. (https://doi.org/10.2106/00004623-199173030-00004)

25. Swentik A, Tucker M & Jones T. Percutaneous application of a medial plate for dual plate stabilization of supracondylar femur fractures. *Journal of Orthopaedic Trauma* 2018 **32** e31–e35. (https://doi.org/10.1097/BOT.0000000000001019)

26. Ziran BH, Rohde RH & Wharton AR. Lateral and anterior plating of intra-articular distal femoral fractures treated via an anterior approach. *International Orthopaedics* 2002 **26** 370–373. (https://doi.org/10.1007/s00264-002-0383-z)

27. Dugan TR, Hubert MG, Siska PA, Pape HC & Tarkin IS. Open supracondylar femur fractures with bone loss in the polytraumatized patient – timing is everything! *Injury* 2013 **44** 1826–1831. (https://doi.org/10.1016/j.injury.2013.03.018)

28. Beeres FJP, Emmink BL, Lanter K, Link BC & Babst R. Minimally invasive double-plating osteosynthesis of the distal femur. *Operative Orthopädie und Traumatologie* 2020 **32** 545–558. (https://doi.org/10.1007/s00064-020-00664-w)

29. Imam MA, Torieh A & Matthana A. Double plating of intra-articular multifragmentary C3-type distal femoral fractures through the anterior approach. *European Journal of Orthopaedic Surgery and Traumatology* 2018 **28** 121–130. (https://doi.org/10.1007/s00590-017-2014-9)

30. Khalil Ael Ael-S & Ayoub MA. Highly unstable complex C3-type distal femur fracture: can double plating via a modified Olerud extensile approach be a standby solution? *Journal of Orthopaedics and Traumatology* 2012 **13** 179–188. (https://doi.org/10.1007/s10195-012-0204-0)

31. Metwaly RG & Zakaria ZM. Single-incision double-plating approach in the management of isolated, closed osteoporotic distal femoral fractures. *Geriatric Orthopaedic Surgery and Rehabilitation* 2018 **9** 2151459318799856. (https://doi.org/10.1177/2151459318799856)

32. Steinberg EL, Elis J, Steinberg Y, Salai M & Ben-Tov T. A double-plating approach to distal femur fracture: a clinical study. *Injury* 2017 **48** 2260–2265. (https://doi.org/10.1016/j.injury.2017.07.025)

33. Bai Z, Gao S, Hu Z & Liang A. Comparison of clinical efficacy of lateral and lateral and medial double-plating fixation of distal femoral fractures. *Scientific Reports* 2018 **8** 4863. (https://doi.org/10.1038/s41598-018-23268-8)

34. Bologna MG, Claudio MG, Shields KJ, Katz C, Salopek T & Westrick ER. Dual plate fixation results in improved union rates in comminuted distal femur fractures compared to single plate fixation. *Journal of Orthopaedics* 2020 **18** 76–79. (https://doi.org/10.1016/j.jor.2019.09.022)

35. Sun R, Zhang Y & Yu Z. Clinical efficacy of augmented medial assisted plate for treating comminuted metaphyseal fracture of the distal femur. *International Journal of Clinical and Experimental Medicine* 2018 **11** 3859–3865.

36. Zhuang Y, Gan Y, Shi D, Tang J, Zhao J & Dai K. Double plating for the treatment of comminuted distal femur fractures with medial instability. *Journal of Orthopedic Research and Therapy* 2018 **2018** JORT-1107. (https://doi.org/10.29011/2575-8241. 001107)

37. Prince JM, Bernatz JT, Binkley N, Abdel MP & Anderson PA. Changes in femoral bone mineral density after total knee arthroplasty: a systematic review and meta-

analysis. *Archives of Osteoporosis* 2019 **14** 23. (https://doi.org/10.1007/s11657-019-0572-7)

38. He QF, Wang HX, Sun H, Zhan Y, Zhang BB, Xie XT & Luo CF. Medial open-wedge osteotomy with double-plate fixation for Varus malunion of the distal femur. *Orthopaedic Surgery* 2019 **11** 82–90. (https://doi.org/10.1111/os.12421)

39. Seligson D. Treatment of supracondylar fractures of the femur. *Journal of Trauma* 2000 **49** 360. (https://doi.org/10.1097/00005373-200008000-00031)

40. Rollick NC, Gadinsky NE, Klinger CE, Kubik JF, Dyke JP, Helfet DL & Wellman DS. The effects of dual plating on the vascularity of the distal femur.pdf. *Bone and Joint Journal* 2020 **102-B** 530–538. (https://doi.org/10.1302/0301-620X.102B4.BJJ-2019-1776)

41. Jiamton C & Apivatthakakul T. The safety and feasibility of minimally invasive plate osteosynthesis (MIPO) on the medial side of the femur: a cadaveric injection study. *Injury* 2015 **46** 2170–2176. (https://doi.org/10.1016/j.injury.2015.08.032)

42. Liporace FA & Yoon RS. Nail plate combination technique for native and periprosthetic distal femur fractures. *Journal of Orthopaedic Trauma* 2019 **33** e64–e68. (https://doi.org/10.1097/BOT.0000000000001332)

43. Mirick Mueller GE. Nail-plate constructs for periprosthetic distal femur fractures. *Journal of Knee Surgery* 2019 **32** 403–406. (https://doi.org/10.1055/s-0039-1683444)

44. Basci O, Karakasli A, Kumtepe E, Guran O & Havitcioglu H. Combination of anatomical locking plate and retrograde intramedullary nail in distal femoral fractures: comparison of mechanical stability. *Eklem Hastalik Cerrahisi* 2015 **26** 21–26. (https://doi.org/10.5606/ehc.2015.06)

45. Attum B, Douleh D, Whiting PS, White-Dzuro GA, Dodd AC, Shen MS, Mir HR, Obremskey WT & Sethi MK. Outcomes of distal femur nonunions treated With a combined nail/plate construct and autogenous bone grafting. *Journal of Orthopaedic Trauma* 2017 **31** e301–e304. (https://doi.org/10.1097/BOT.0000000000000926)

46. Egol KA, Delsole E, Mandel J & Konda S. Repair of distal femoral periprosthetic nonunion: linked nail plate construct. *Journal of Orthopaedic Trauma* 2019 **33** (Supplement 1) S30–S31. (https://doi.org/10.1097/BOT.0000000000001549)

47. Hussain MS, Dailey SK & Avilucea FR. Stable fixation and immediate weight-bearing after combined retrograde intramedullary nailing and open reduction internal fixation of noncomminuted distal interprosthetic femur fractures. *Journal of Orthopaedic Trauma* 2018 **32** e237–e240. (https://doi.org/10.1097/BOT.0000000000001154)

48. Kanabur P, Sandilands SM, Whitmer KK, Owen TM, Coniglione FM & Shuler TE. Nail and locking plate for periprosthetic fractures. *Journal of Orthopaedic Trauma* 2017 **31** e425–e431. (https://doi.org/10.1097/BOT.0000000000000939)

49. Choi YS & Kim KS. Plate augmentation leaving the nail in situ and bone grafting for non-union of femoral shaft fractures. *International Orthopaedics* 2005 **29** 287–290. (https://doi.org/10.1007/s00264-005-0668-0)

50. Nadkarni B, Srivastav S, Mittal V & Agarwal S. Use of locking compression plates for long bone nonunions without removing existing intramedullary nail: review of literature and our experience. *Journal of Trauma* 2008 **65** 482–486. (https://doi.org/10.1097/TA.0b013e31817c9905)

51. Ueng SW, Chao EK, Lee SS & Shih CH. Augmentative plate fixation for the management of femoral nonunion after intramedullary nailing. *Journal of Trauma* 1997 **43** 640–644. (https://doi.org/10.1097/00005373-199710000-00013)

52. Birjandinejad A, Ebrahimzadeh MH & Ahmadzadeh-Chabock H. Augmentation plate fixation for the treatment of femoral and tibial nonunion after intramedullary nailing. *Orthopedics* 2009 **32** 409. (https://doi.org/10.3928/01477447-20090511-12)

53. Ueng SW & Shih CH. Augmentative plate fixation for the management of femoral nonunion with broken interlocking nail. *Journal of Trauma* 1998 **45** 747–752. (https://doi.org/10.1097/00005373-199810000-00021)

54. Lee KH, Kim HM, Moon CW, Kim YS & Nam WS. Augmentation plate fixation for the management of long-bone nonunion after intramedullary nailing. *Journal of the Korean Fracture Society* 2004 **17** 265–270. (https://doi.org/10.12671/jkfs.2004.17.3.265)

55. Spitler CA, Bergin PF, Russell GV & Graves ML. Endosteal substitution With an intramedullary rod in fractures of the femur. *Journal of Orthopaedic Trauma* 2018 **32** (Supplement 1) S25–S29. (https://doi.org/10.1097/BOT.0000000000001094)

56. Garnavos C, Lygdas P & Lasanianos NG. Retrograde nailing and compression bolts in the treatment of type C distal femoral fractures. *Injury* 2012 **43** 1170–1175. (https://doi.org/10.1016/j.injury.2012.03.023)