



# External fixation to intramedullary nailing for femoral and tibial fractures: an eleven-year cohort study at a level I trauma center

Diego González-Morgado<sup>1,2</sup> · Paula Fabado-Tortajada<sup>2</sup> · Josep Nomdedéu<sup>1,2</sup> · Jordi Teixidor-Serra<sup>1,2</sup> · Jordi Tomàs-Hernández<sup>2</sup> · Nayana Joshi-Jubert<sup>1,2</sup> · Joan Minguell-Monyart<sup>1,2</sup> · José Vicente Andrés-Peiró<sup>1,2</sup>

Received: 13 December 2024 / Accepted: 30 March 2025 / Published online: 27 May 2025  
© The Author(s) 2025

## Abstract

**Purpose** To identify factors that contribute to the incidence of postoperative complications following staged treatment of femoral and tibial fractures with external fixation (EF) and intramedullary nailing (IMN).

**Methods** This retrospective cohort study involved patients with tibial and/or femoral fractures temporarily immobilized using EF, followed by IMN. Patient characteristics, types of injury, treatments, and outcomes were recorded. Primary outcomes were pin tract infection (PTI) and fracture-related infection (FRI).

**Results** The study had 103 patients involving 119 fractures: 73 tibial (61.3%) and 46 femoral (38.7%). Of these, 44.5% were open. 31.1% of the EFs were implanted by an orthopedic trauma (OT) specialist. In femoral fractures, OT specialists placed the pins a mean 78.2 mm from the fracture site, versus just 37.3 mm by non-OT surgeons ( $p < 0.01$ ). This difference was not observed in the tibia. The average time of EF was  $12.6 \pm 7.8$  days. PTI occurred in seven cases (5.9%), on average  $14.9 \pm 10.9$  days after EF placement. FRI occurred in nine patients (7.6%): two in the femur (4.5%) and seven in the tibia (10.6%). All FRIs occurred in cases where the EF had been implanted by a surgeon without specialization in OT ( $p = 0.03$ ). FRI was more frequent in patients with prior PTI than in those without (57.1% vs. 4.5%, respectively;  $p < 0.01$ ).

**Conclusion** PTI was a risk factor for FRI after IMN of tibial and femoral fractures. Surgeon specialization in OT was a protective factor against FRI, probably related to pin placement further from the fracture site.

**Keywords** Intramedullary nailing · External fixation · Femur fracture · Tibia fracture · Pin tract infection · Fracture-related infection

## Introduction

Intramedullary nailing (IMN) is the standard treatment for diaphyseal fractures of the tibia and femur [1, 2]. These fractures often occur in polytrauma patients with life-threatening injuries or severe soft tissue damage. In such cases, a damage control orthopedics approach with external fixation (EF)

temporarily stabilizes the fractures while minimizing the burden of a more extensive surgical procedure [3, 4].

Infection following IMN is a devastating complication [5–7]. Although the use of previous EF has been shown to increase complication risk in several series [8–12], understanding of the factors that contribute to postoperative complications following this staged strategy is limited.

✉ José Vicente Andrés-Peiró  
josevicente.andres@uab.cat

Diego González-Morgado  
diegoglezmorgado@gmail.com

Paula Fabado-Tortajada  
paula.fabado@gmail.com

Josep Nomdedéu  
nomdedeu7@gmail.com

Jordi Teixidor-Serra  
jteixidorserra@gmail.com

Jordi Tomàs-Hernández  
tomjordi@gmail.com

Nayana Joshi-Jubert  
njoshijubert@gmail.com

Joan Minguell-Monyart  
minguell.traumatologia@gmail.com

<sup>1</sup> Department of Surgery, Universitat Autònoma de Barcelona, Barcelona, Spain

<sup>2</sup> Vall d'Hebron Hospital Universitari, Barcelona, Spain

The primary aim of this study was to identify factors that contribute to postoperative complications following staged treatment with EF and IMN for femoral and tibial fractures. We hypothesized that the development of pin tract infection (PTI) and a reduced pin-to-fracture site distance would increase the rate of fracture-related infection (FRI). Additionally, we examined the impact of the treating surgeon's training on treatment modalities and postoperative outcomes.

## Methods

This retrospective cohort study (level of evidence III) examined patients treated at a single level I trauma center between March 2011 and November 2022. We recruited all skeletally-mature patients (age  $\geq 15$  years) with femoral and/or tibial fractures who underwent temporary EF followed by IMN. We excluded cases involving indications for EF or IMN other than acute fracture fixation, pathological fractures, refractures, and any history of infection or neoplasms around the femur or tibia or their adjacent joints. To directly assess the impact of medullary cavity instrumentation by the pins, we also excluded patients who experienced a latency period between removal of the fixator and the nailing ("pin holidays") and those in whom there was no overlap between the trajectories of the intramedullary implant and fixator pins. Institutional Review Board approval was obtained prior to study commencement (PR(AT)233/2022), and we adhered to the STROBE statement. Postoperative follow-up occurred over a one-year period.

All EFs were applied emergently as part of a damage control orthopedics approach, either local or systemic, by on-call orthopedic surgeons with varying levels of specialization in orthopedic trauma (OT). All definitive surgeries were conducted exclusively by OT surgeons. Open fracture management involved prompt antibiotic administration, debridement, and irrigation. When primary closure of wounds was infeasible, negative pressure wound therapy was utilized. The decision to use local antibiotics was made by attending surgeons. Open wound coverage was performed in collaboration with plastic surgeons. The EF pins underwent daily cleaning and antisepsis, per hospital guidelines. Conversion from EF to IMN was performed as soon as safely possible.

Fractures were classified using the AO/OTA system on emergency radiographs. The distance from the nearest EF pin to the closest fractured cortex on post-EF radiographs determined the pin-to-fracture distance. These same radiographs were used to measure the distance from the nearest pin to the center of rotation of the femoral head, the superior pole of the patella, or the center of the tibial eminence, and the talar articular surface, to assess the pin-to-hip, pin-to-knee, and pin-to-ankle distances, respectively. In

radiographs following IMN, the degree of overlap of the nail with the EF's pin trajectory was assessed. Each image was evaluated once by a single investigator blinded to outcomes.

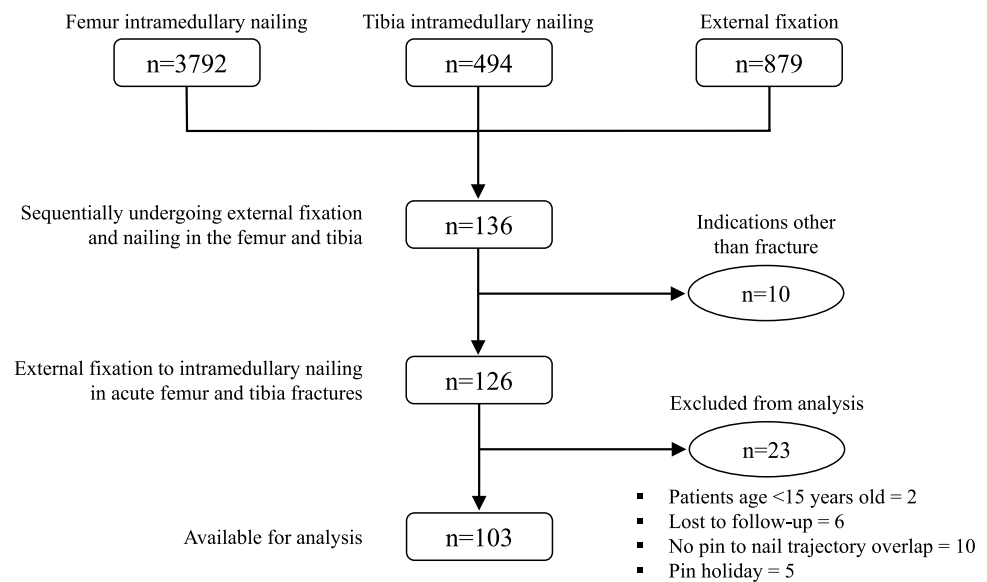
We collected data on patient characteristics, their injuries, treatment provided, radiological evaluation, and outcomes. The primary outcome was the diagnosis of PTI and/or FRI based on clinical, radiological, and laboratory criteria [13, 14]. Secondary outcomes included any other postoperative complication.

Statistical analysis was performed using Stata/IC 14.2 (StataCorp, College Station, TX, USA). Continuous variables were summarized using means and standard deviations or medians and interquartile ranges (IQR), as appropriate. Categorical variables were represented using counts and percentages (%). To assess differences between continuous variables, the Student's t-test or Wilcoxon-Mann-Whitney rank-sum test were used, depending on data distribution. For categorical variables, differences were evaluated using the Pearson chi-square or Fisher's exact test, as appropriate. All  $p$ -values  $< 0.05$  were considered statistically significant.

## Results

A total of 103 patients of mean age  $41.3 \pm 18.8$  years, with 119 fractures, were included (Fig. 1). Most patients were male (68%) and were predominantly involved in a traffic accident (60.2%), with a median Injury Severity Score (ISS) of 18 (IQR = 34). Among the 119 fractures, 73 were tibial (61.3%) and 46 femoral fractures (38.7%). Four patients had bilateral femur fractures, and two had bilateral tibia fractures. Nine patients had a floating knee, one being bilateral. We identified 53 open fractures (44.6%), more commonly in the tibia (54.8% tibia vs. 28.3% femur;  $p < 0.01$ ). Gustilo IIIB fractures were prevalent in the tibia, accounting for 30% of open fractures in that bone (12 cases). Seventeen open fractures had a bone defect (32.1%), deemed critical or subcritical in eight cases [15]. Compartment syndrome requiring fasciotomy occurred in four cases (3.4%), three for the femur and one the tibia. Blisters were observed in 16 (21.9%) of the 73 tibial fractures, occurring in patients with a lower ISS (8.9 vs. 24.1;  $p < 0.01$ ). Table 1 summarizes the study participants and their injuries.

An orthopedic trauma (OT) specialist implanted 31.1% of the EFs. Roughly half (46.2%) the fixators were applied in a joint-spanning configuration. Spanning frames predominated in tibial over femoral fractures (61.6 vs. 21.7%;  $p < 0.01$ ). In the tibia, spanning frames were used more frequently by OT surgeons (42.9% vs. 12.5% for non-OT specialists;  $p < 0.02$ ). The average minimum pin-to-fracture distance was  $63.3 \pm 44.6$  mm, being significantly longer for tibial than femoral fractures (71.8 vs. 49.7 mm;  $p < 0.01$ ) and for spanning than sparing frames (92.9 vs. 37.8 mm;  $p < 0.01$ ). For

**Fig. 1** Flow diagram depicting patient selection process

femoral fractures, OT specialists placed the pins an average of 78.2 mm from the fracture site, compared to 37.3 mm by non-OT surgeons ( $p < 0.01$ ). Such a difference was not observed in the tibia. The mean minimum distance from the pins to the femoral head was  $131.9 \pm 57.6$  mm:  $92.6 \pm 42.6$  mm to the knee (superior pole of the patella or the tibial eminence), and  $66.6 \pm 50.6$  mm to the ankle. This distance was consistently greater with spanning configurations than sparing frames: 200.3 vs. 114.7 mm at the hip, 115.1 vs. 74.3 mm at the knee, and 92.4 vs. 49.4 mm at the ankle, respectively (all  $p < 0.01$ ). No cases of septic arthritis were identified; therefore, no association was found between this complication and the proximity of pins to joints. The average time of EF was  $12.6 \pm 7.8$  days, though appreciably longer in patients undergoing a fasciotomy (33.5 vs. 11.9 days;  $p < 0.01$ ). In 11 of 53 open fractures, local antibiotics were used, mainly in cases involving bone defects (29.4%) and Gustilo III open fractures (36.3%). PTI occurred in 5.9% of the EFs. No association was identified between this adverse event and patient characteristics, injury specifics, pin or frame configuration, surgeon's profile or EF duration. PTIs appeared an average of  $14.9 \pm 10.9$  days after EF. Diagnosis was primarily clinical, with microbiological confirmation in only three of seven cases (Table 2).

Diaphyseal fractures (AO/OTA 32 and 42) were the primary indication for IMN in both the femur (93.5%) and tibia (82.2%). Among these diaphyseal fractures, 44.2% in the femur and 34.2% in the tibia were classified as segmental fractures (AO/OTA 32 C and 42 C). Nineteen retrograde and 26 antegrade IMNs were implanted in the femur, 20 of the latter being cephalomedullary. In the tibia, 70 suprapatellar and three retrograde IMNs were implanted for tibiototalcanal fusion. Open reduction was required for 21.9% of fractures before nail insertion, more often in

the femur (37.0% vs. 12.3% for tibia;  $p < 0.01$ ). On average,  $3.1 \pm 1.0$  pinholes overlapped with the trajectory of the IMN. The number of pins that overlapped the nail was significantly greater in the femur than tibia (3.5 vs. 2.9;  $p < 0.01$ ) and for non-spanning than spanning frames (3.9 vs. 2.2;  $p < 0.01$ ). All Gustilo IIIB fractures were covered with a free flap, with 11 undergoing "fix and flap" within a median of nine days (IQR = 6). In the remaining three, coverage was initially performed on EF, followed by conversion to IMN. The three critical bone defects, one in the femur and two in the tibia, were managed using an induced membrane technique.

We identified nine FRIs (7.6% of fractures): two in the femur (4.5%) and seven in the tibia (10.6%) (Table 2). All FRIs occurred in cases where the EF had been implanted by a non-OT surgeon ( $p = 0.03$ ). FRI was more frequent in patients with prior PTI than in those without (57.1% vs. 4.5%, respectively;  $p < 0.01$ ). In two FRIs with a history of PTI, the microbiological diagnosis was the same for each (*E. cloacae*). In the tibia, the minimum distance from the pins to fracture site was shorter in cases with an FRI (42 mm vs. 74.9 mm); however, this difference was not statistically significant ( $p = 0.07$ ). The presence of blisters was associated with an increased incidence of tibial FRI (57.1% vs. 18.2%, respectively;  $p < 0.04$ ). Neither the presence of an open fracture nor the time to flap influenced the risk of FRI. FRIs appeared a median of 222 days after nailing (IQR = 221.5). In six of nine cases, treatment required removing the IMN. We found two aseptic non-unions caused by mechanical problems, one in the femur and one in the tibia, which needed revision of fixation surgery. All remaining fractures healed within the study period. Joint stiffness in the knee developed in seven cases, with four involving femoral and three tibial fractures.

**Table 1** Patient's characteristics, injuries, treatments, and outcomes

		Femur	Tibia	Overall	
Patients and injuries	Sex (male/female)	73.9/26.1	64.4/35.6	68.1/31.9	
	Age (years)	33.7 ± 13.3	44.0 ± 19.7	41.3 ± 18.8	
	CCI <sup>a</sup>	0.2 ± 0.9	0.9 ± 1.8	0.6 ± 1.5	
	ISS <sup>b</sup>	43.8 ± 18.2	20.7 ± 20.1	29.6 ± 22.4	
	Open fractures	28.3	54.8	44.5	
	<i>Gustilo classification</i>				
	I	–	11.0	6.7	
	II	–	19.2	11.8	
	IIIA	26.1	6.9	14.3	
	IIIB	2.2	16.4	10.9	
	IIIC	–	1.4	0.8	
	<i>Bone defect classification [13]</i>				
	D1	4.4	9.6	7.6	
	D2	6.5	2.7	4.2	
	D3	–	4.1	2.5	
	Compartment syndrome	6.5	1.4	3.4	
	Surgical treatment	Spanning frame	21.7	61.6	46.2
		Hip	8.7	–	3.4
		Knee	15.2	13.7	14.3
		Ankle	–	49.3	30.3
Pin-to-fracture distance (mm) <sup>c</sup>		49.7 ± 41.5	71.8 ± 44.7	63.3 ± 44.6	
<i>Pin-to-joint distance (mm)<sup>d</sup></i>					
Hip		131.9 ± 57.6	–	131.9 ± 57.6	
Knee		77.0 ± 39.9	102.0 ± 41.7	92.6 ± 42.6	
Ankle		–	66.6 ± 50.6	66.6 ± 50.6	
Time of EF (days) <sup>e</sup>		12.3 ± 8.5	12.8 ± 7.3	12.6 ± 7.8	
Open reduction		37.0	12.3	21.9	
Pin-to-nail overlap <sup>f</sup>		3.5 ± 0.9	2.9 ± 1.1	3.1 ± 1	
Outcomes	Pin-tract infection	4.4	6.9	5.9	
	Fracture-related infection	4.4	9.6	7.6	

Categorical variables are represented as percentages (%), and continuous variables as mean ± standard deviation

<sup>a</sup>Charlson's Comorbidity Index

<sup>b</sup>Injury Severity Score

<sup>c</sup>Distance from the nearest EF pin to the closest fractured cortex on post-EF radiographs

<sup>d</sup>Distance from the nearest pin to the center of rotation of the femoral head, the superior pole of the patella or the center of the tibial eminence, and the talar articular surface on post-EF radiographs

<sup>e</sup>Days taken from external fixator application to intramedullary nailing

<sup>f</sup>Overlap of the nail with the EF's pin trajectory on post-IMN radiographs

## Discussion

In this study of 119 femoral and tibial fractures sequentially treated with EF and IMN, we observed a 5.9% incidence of PTI and 7.6% incidence of FRI, potentially highlighting a relationship between these complications. Notably, the use of EF by a surgeon specialized in orthopedic trauma (OT) was identified as a protective factor against infection.

Fractures of the tibia and femur that occur in polytrauma patients often require a damage control orthopedics strategy

with EF followed by IMN [3, 4]. The timing of conversion is influenced by several factors, including soft tissue condition, need for further debridement, EF pin condition, and the patient's physiological state [16]. Delaying definitive surgery to the 6th to 8th day has been shown to decrease the inflammatory response relative to earlier intervention [3]. In our study, the time to IMN conversion was longer than 6–8 days and quite variable, likely due to both significant trauma-related systemic involvement and local conditions in the affected extremity, as seen in the high rates of open fractures

**Table 2** Clinical and microbiological profiles of pin-tract and fracture-related infections

Sex, age <sup>a</sup>	ISS <sup>b</sup>	AO/OTA <sup>c</sup>	Gustilo <sup>d</sup>	PTI	FRI			Microbiology	Management <sup>h</sup>
					EF to PTI onset <sup>e</sup>	Clinical criteria	Laboratory		
M, 19	75	32B	9		Painful, purulent drainage	CoNS <sup>f</sup> + <i>E. coli</i>			
F, 35	48	31B	18		Persistent or increasing drainage				
M, 40	9	41 C	34 (after EF removal)	IIIA	Spreading erythema				
F, 71	9	42 C	8		Persistent or increasing drainage	<i>E. cloacae</i>	222	Fistula	<i>E. cloacae</i> NR + RIA + AB IMN + flap
F, 88	9	44B	6		Local pain		106	Clinical signs + elevated serum markers	<i>E. cloacae</i> NR + RIA
M, 30	9	42 C	24		Painful, purulent drainage	<i>E. cloacae</i>	33	Clinical signs + elevated serum markers	<i>E. cloacae</i> NR + RIA + circular frame
M, 32	75	43B	5		Spreading erythema		312	Radiological signs (non-union)	<i>C. acnes</i> NR + RIA + AB IMN
F, 46	43	42 C	II				315	Clinical signs + elevated serum markers	CoNS <sup>f</sup> NR + RIA
M, 41	9	42 C					299	Clinical signs + elevated serum markers	<i>E. cloacae</i> NR + RIA + AB IMN
M, 34	75	32 A					217	Fistula	<i>E. coli</i> DAIR
M, 16	18	32 A					62	Clinical signs + elevated serum markers	<i>C. acnes</i> DAIR
M, 63	9	42 A	IIIB				241	Clinical signs + elevated serum markers	CoNS <sup>f</sup> DAIR

<sup>a</sup>Shown as: M (male)/F (female), age (years)

<sup>b</sup>Injury Severity Score

<sup>c</sup>AO/OTA fracture classification

<sup>d</sup>Gustilo classification for open fractures. Empty for closed injuries

<sup>e</sup>Days from EF application to PTI onset

<sup>f</sup>Coagulase-negative Staphylococci

<sup>g</sup>Days from IMN to FRI onset

<sup>h</sup>NR: nail removal; RIA: reamer irrigator aspirator debridement; AB IMN: antibiotic-coated IMN; DAIR: debridement and implant retention

and soft tissue damage. This highlights the heterogeneity of these patients and the need for an individualized approach when determining the optimal timing for definitive surgery.

Local infection attributed to EF is the most commonly argued downside of this staged treatment [17]. In most studies, PTI rates were between 5 and 25% [8, 17–19], consistent with our findings. Although the risk factors for PTI are not fully understood, it is recommended that surgeons carefully select their pin sites and avoid areas with soft tissue damage [19–22]. Prolonged EF duration can also contribute to PTI, as extended exposure increases the risk of bacterial colonization [19–22]. For instance, PTI and postoperative infection rates rise significantly when EF remains in place for more than 2 weeks [8, 9, 17, 23]. Our low PTI rate was likely due to early conversion to IMN, within two weeks in most cases, and strict adherence to a standardized pin-care protocol. Although proper pin care is likely crucial, there is currently no consensus on best practices [21, 22, 24, 25]. While additional preventative options for PTI, including pin coating, exist [19], further measures to prevent PTI remain necessary.

The incidence of FRI following IMN of the tibia and femur has ranged widely, from 1 to 23% [5–7], being higher after conversion from EF (6–67%) [8–12, 18], thereby aligning with our findings. Several factors contribute to FRI, including fracture type, open fractures, prior use of EF, and the need for soft tissue reconstruction [5, 6, 9, 10]. Similarly, we found an association between FRI and PTI, as well as soft tissue damage. Conversely, we failed to identify any association with the duration of EF, open fractures, or other injury characteristics.

Several strategies have been proposed to reduce FRI after EF [9, 12, 17, 18, 23–33]. While early conversion to IMN as a single procedure is generally recommended [9, 12, 26], some authors advocate for a two-stage conversion or “pin-holiday” approach [29, 31–33], especially when a PTI is present [10, 11, 18, 28]. Additional preventative measures include pin track debridement, soft tissue excision, over-drilling of bony pin holes, and administering antibiotics when PTI first becomes evident [9, 17, 27]. While we generally avoided two-stage conversions, we applied these additional measures during IMN conversion when PTI was suspected or when conversion occurred more than two weeks after external EF. Other authors have recommended performing systematic cultures of the IMN reaming and subsequent use of postoperative antibiotics based on final culture results [12]. However, their high number of contaminated samples raises concerns about the reliability of this practice [12]. We found that microbiological organism remained the same in two patients who developed FRI after PTI, agreeing with Bunzel et al.’s findings [9]. This highlights the risk of bacteria migrating from EF pin sites into the intramedullary canal, potentially

causing deep postoperative infections, emphasizing the need for careful patient selection when using EF in fractures likely to need IMN later.

While the principles for pin placement in EF for fracture stability are well established, research on how pin placement affects consolidation and infection is limited [16, 34]. Although it is generally recommended that surgeons avoid placing pins in areas of soft-tissue damage or fracture hematoma, how the distance from the pin to fracture site impacts outcomes has not been thoroughly investigated. We found that patients with tibial fractures who developed FRI had pins placed closer to the fracture site. Although this finding did not reach statistical significance, this may merely have been because of inadequate statistical power. Proximity to the injury or fracture hematoma can increase the risk of PTI due to higher contamination levels in these areas, particularly with open fractures. Additionally, pins placed too close to the fracture site may disrupt local soft tissue and periosteal blood supply, which are crucial for bone healing and infection resistance [35].

Previous studies on ankle and tibial plateau fractures have revealed that surgeon specialization does not influence EF placement or postoperative outcomes [36, 37]. Conversely, in our study, the use of EF by a surgeon specialized in OT was protective against infection, likely due to more refined surgical techniques and greater adherence to maintaining safe distances between pins and fracture sites, which was probably facilitated by the more frequent use of joint-spanning frames. Notably, all FRIs occurred in patients managed by non-OT surgeons. These findings emphasize the importance of advanced training in EF for orthopedic surgeons to ensure optimal temporary fracture stability while minimizing the risk of infectious complications.

We acknowledge several limitations of this study, including its retrospective design, the heterogeneity of the injuries (encompassing both femoral and tibial fractures, open and closed), and the diversity of treatment modalities employed. Despite these limitations, the study offers clinically relevant insights by demonstrating a strong association between prior pin tract infection and fracture-related infection, identifying surgeon specialization as a protective factor, and introducing pin-to-fracture distance as a potentially modifiable surgical variable. These findings are supported by an integrated analysis of radiological, microbiological, and surgical data from a large real-world cohort, enhancing the robustness and clinical value of our results.

In conclusion, prior pin-tract infection appears to significantly increase the risk of fracture-related infection after intramedullary nailing of tibial and femoral fractures. Conversely, specialization in orthopedic trauma may be protective against infections, likely due to more strategic pin-site selection.

**Acknowledgements** This work has been carried out within the framework of the PhD in Surgery and Morphological Sciences at Universitat Autònoma de Barcelona. No funding was received for conducting this study.

**Author contributions** All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by the research team. The first draft of the manuscript was written by two of the authors, and all authors reviewed and commented on previous versions. All authors read and approved the final manuscript.

**Funding** Open Access Funding provided by Universitat Autònoma de Barcelona.

**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Conflict of interest** The authors declare financial conflicts of interest with Smith & Nephew, Zimmer-Biomet, Stryker, Link Orthopaedics, Arthrex, and MBA Surgical Empowerment.

**Consent to participate** This is a retrospective study, which did not involve any risk to participants, and all collected data were de-identified. Therefore, the IRB granted a full waiver of informed consent.

**Ethical approval** This study was approved by our institutional review board (reference number PR(ATR)121/2021).

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Bekos A, Sioutis S, Kostroglou A et al (2021) The history of intramedullary nailing. *Int Orthop* 45:1355–1361. <https://doi.org/10.1007/s00264-021-04973-y>
- Bong MR, Kummer FJ, Koval KJ, Egol KA (2007) Intramedullary nailing of the lower extremity: biomechanics and biology. *J Am Acad Orthop Surg* 15:97–106. <https://doi.org/10.5435/00124635-200702000-00004>
- Roberts CS, Pape H-C, Jones AL et al (2005) Damage control orthopaedics: evolving concepts in the treatment of patients who have sustained orthopaedic trauma. *Instr Course Lect* 54:447–462
- Hildebrand F, Giannoudis P, Krettek C, Pape H-C (2004) Damage control: extremities. *Injury* 35:678–689. <https://doi.org/10.1016/j.injury.2004.03.004>
- Oliveira PR, Leonhardt MC, Carvalho VC et al (2018) Incidence and risk factors associated with infection after intramedullary nailing of femoral and tibial diaphyseal fractures: Prospective study. *Injury* 49:1905–1911. <https://doi.org/10.1016/j.injury.2018.07.024>
- Metsemakers W-J, Handoyo K, Reynders P et al (2015) Individual risk factors for deep infection and compromised fracture healing after intramedullary nailing of tibial shaft fractures: a single centre experience of 480 patients. *Injury* 46:740–745. <https://doi.org/10.1016/j.injury.2014.12.018>
- Galvin JW, Dannenbaum JH, Tubb CC et al (2015) Infection rate of intramedullary nailing in closed fractures of the femoral diaphysis after temporizing external fixation in an austere environment. *J Orthop Trauma* 29:e316–320. <https://doi.org/10.1097/BOT.0000000000000327>
- Bhandari M, Zlowodzki M, Tornetta P et al (2005) Intramedullary nailing following external fixation in femoral and tibial shaft fractures. *J Orthop Trauma* 19:140–144. <https://doi.org/10.1097/00005131-200502000-00012>
- Bunzel EW, Wilkinson B, Rothberg D et al (2023) Conversion of external fixator to intramedullary nail in Tibial fractures. *J Am Acad Orthop Surg* 31:41–48. <https://doi.org/10.5435/JAAOS-D-21-00857>
- Yokoyama K, Itoman M, Uchino M et al (2008) Immediate versus delayed intramedullary nailing for open fractures of the tibial shaft: a multivariate analysis of factors affecting deep infection and fracture healing. *Indian J Orthop* 42:410–419. <https://doi.org/10.4103/0019-5413.43385>
- Pairon P, Ossendorf C, Kuhn S et al (2015) Intramedullary nailing after external fixation of the femur and tibia: a review of advantages and limits. *Eur J Trauma Emerg Surg* 41:25–38. <https://doi.org/10.1007/s00068-014-0448-x>
- Roussignol X, Sigonney G, Potage D et al (2015) Secondary nailing after external fixation for tibial shaft fracture: risk factors for union and infection. A 55 case series. *Orthop Traumatol Surg Res* 101:89–92. <https://doi.org/10.1016/j.otsr.2014.10.017>
- Frank FA, Stubbs D, Ferguson JY, McNally M (2024) A practical definition of pin site infection. *Injury* 55:111230. <https://doi.org/10.1016/j.injury.2023.111230>
- Metsemakers WJ, Morgenstern M, McNally MA et al (2018) Fracture-related infection: a consensus on definition from an international expert group. *Injury* 49:505–510. <https://doi.org/10.1016/j.injury.2017.08.040>
- Tetsworth KD, Burnand HG, Hohmann E, Glatt V (2021) Classification of bone defects: an extension of the orthopaedic trauma association open fracture classification. *J Orthop Trauma* 35:71. <https://doi.org/10.1097/BOT.0000000000001896>
- Bible JE, Mir HR (2015) External fixation: principles and applications. *J Am Acad Orthop Surg* 23:683–690. <https://doi.org/10.5435/JAAOS-D-14-00281>
- Harwood PJ, Giannoudis PV, Probst C et al (2006) The risk of local infective complications after damage control procedures for femoral shaft fracture. *J Orthop Trauma* 20:181–189. <https://doi.org/10.1097/00005131-200603000-00004>
- Yokoyama K, Uchino M, Nakamura K et al (2006) Risk factors for deep infection in secondary intramedullary nailing after external fixation for open tibial fractures. *Injury* 37:554–560. <https://doi.org/10.1016/j.injury.2005.08.026>
- Parameswaran AD, Roberts CS, Seligson D, Voor M (2003) Pin tract infection with contemporary external fixation: how much of a problem? *J Orthop Trauma* 17:503–507. <https://doi.org/10.1097/00005131-200308000-00005>
- Mahan J, Seligson D, Henry SL et al (1991) Factors in pin tract infections. *Orthopedics* 14:305–308
- Ktistakis I, Guerado E, Giannoudis PV (2015) Pin-site care: can we reduce the incidence of infections? *Injury* 46(Suppl 3):S35–39. [https://doi.org/10.1016/S0020-1383\(15\)30009-7](https://doi.org/10.1016/S0020-1383(15)30009-7)

22. Guerado E, Cano JR, Fernandez-Sanchez F (2019) Pin tract infection prophylaxis and treatment. *Injury* 50(Suppl 1):S45–S49. <https://doi.org/10.1016/j.injury.2019.03.044>
23. Ye Z, Zhao S, Zeng C et al (2021) Study on the relationship between the timing of conversion from external fixation to internal fixation and infection in the treatment of open fractures of extremities. *J Orthop Surg Res* 16:662. <https://doi.org/10.1186/s13018-021-02814-7>
24. Ferguson D, Harwood P, Allgar V et al (2021) The PINS Trial: a prospective randomized clinical trial comparing a traditional versus an emollient skincare regimen for the care of pin-sites in patients with circular frames. *Bone Joint J* 103-B:279–285. <https://doi.org/10.1302/0301-620X.103B2.BJJ-2020-0680.R1>
25. Lethaby A, Temple J, Santy-Tomlinson J (2013) Pin site care for preventing infections associated with external bone fixators and pins. *Cochrane Database Syst Rev*. <https://doi.org/10.1002/14651858.CD004551.pub3>
26. Cheyrou-Lagreze A, Severyns M, Rongieras F et al (2022) Secondary intramedullary nailing for open tibial shaft fractures. Comparison of a one-stage versus two-stage surgical procedure. *Orthop Traumatol Surg Res* 108:103391. <https://doi.org/10.1016/j.otsr.2022.103391>
27. Erdem Y, Neyisci C, Koca K et al (2019) Is staged management with immediate conversion of external fixation to retrograde intramedullary nailing for combat-related gustilo type III supracondylar femur fractures safe and reliable method? *Injury* 50:764–769. <https://doi.org/10.1016/j.injury.2019.01.019>
28. Marshall PD, Saleh M, Douglas DL (1991) Risk of deep infection with intramedullary nailing following the use of external fixators. *J R Coll Surg Edinb* 36:268–271
29. Maurer DJ, Merkow RL, Gustilo RB (1989) Infection after intramedullary nailing of severe open tibial fractures initially treated with external fixation. *J Bone Joint Surg Am* 71:835–838
30. Sigurdson U, Reikeras O, Utvag SE (2011) The effect of timing of conversion from external fixation to secondary intramedullary nailing in experimental tibial fractures. *J Orthop Res* 29:126–130. <https://doi.org/10.1002/jor.21182>
31. Blachut PA, Meek RN, O'Brien PJ (1990) External fixation and delayed intramedullary nailing of open fractures of the tibial shaft. A sequential protocol. *J Bone Joint Surg Am* 72:729–735
32. Antich-Adrover P, Martí-Garin D, Murias-Alvarez J, Puente-Alonso C (1997) External fixation and secondary intramedullary nailing of open tibial fractures. A randomised, prospective trial. *J Bone Joint Surg Br* 79:433–437
33. Wheelwright EF, Court-Brown CM (1992) Primary external fixation and secondary intramedullary nailing in the treatment of tibial fractures. *Injury* 23:373–376. [https://doi.org/10.1016/0020-1383\(92\)90010-p](https://doi.org/10.1016/0020-1383(92)90010-p)
34. Encinas-Ullán CA, Martínez-Diez JM, Rodríguez-Merchán EC (2020) The use of external fixation in the emergency department: applications, common errors, complications and their treatment. *EFORT Open Rev* 5:204–214. <https://doi.org/10.1302/2058-5241.5.190029>
35. Hodgson S (2009) AO principles of fracture management. *Ann R Coll Surg Engl* 91:448–449. <https://doi.org/10.1308/003588409X432419f>
36. Oleo-Taltavull R, Corró S, Tomàs-Hernández J et al (2023) Staged treatment of bicondylar tibial plateau fractures: influence of frame configuration and quality of reduction on outcomes. *Eur J Trauma Emerg Surg*. <https://doi.org/10.1007/s00068-023-02411-9>
37. González-Morgado D, Bargalló-Granero J, Pujol O et al (2024) Temporary immobilization methods for closed low-energy ankle fracture-dislocations: comparative analysis of a retrospective cohort. *Eur J Orthop Surg Traumatol* 34:2457–2464. <https://doi.org/10.1007/s00590-024-03966-y>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.