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Effects of external fixator-assisted acute angulation on arterial diameter: a cadaveric model

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Abstract

Background Open fractures with bone and soft tissue loss pose significant challenges in orthopedic surgery. External fixator-assisted techniques, such as acute angulation and shortening, have been proposed to facilitate wound closure. However, the vascular implications of these techniques remain unclear. This cadaveric study aimed to evaluate the effect of acute angulation on arterial narrowing at the proximal tibia and distal femur, identifying angulation thresholds and comparing the vascular tolerance between these anatomical sites.

Methods Eight lower extremities from four fresh-frozen cadavers were used. Osteotomies were performed at the distal femoral and proximal tibial metaphyses. An Ilizarov circular external fixator provided controlled angulation in varus, valgus, procurvatum, and recurvatum directions. A contrast agent was used for vascular visualization under fluoroscopy. Angulation was gradually increased until arterial narrowing was observed, and the critical angles were recorded.

Results In the proximal tibia, the mean angulation thresholds for arterial narrowing were 45.5° in varus, 26.5° in valgus, 33.8° in procurvatum, and 13.5° in recurvatum. In the distal femur, arterial narrowing occurred at 27° in varus, 32.3° in valgus, 52° in procurvatum, and 22° in recurvatum. Varus angulation was significantly better tolerated at the tibia ($p=0.0286$), while procurvatum ($p=0.0294$) and recurvatum ($p=0.0286$) were better tolerated at the femur. No significant difference was found in valgus angulation ($p=0.559$).

Conclusions The tibia demonstrated higher tolerance for varus angulation, while the femur allowed greater procurvatum and recurvatum before vascular compromise. Recurvatum deformities in the tibia resulted in the earliest arterial narrowing, suggesting a higher risk of vascular complications. These findings provide critical insight for surgeons performing external fixator-assisted soft tissue coverage, helping optimize angulation strategies to prevent vascular complications.

Keywords External fixators, Fractures, Open, Ilizarov technique, Soft tissue injuries, Thrombosis

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Introduction

Open fractures with bone and soft tissue loss present a significant challenge for surgeons. Since the soft tissue integrity is crucial for bone healing, achieving proper alignment of the fracture is not sufficient. Adequate soft tissue coverage is essential not only for successful bone union but also for preventing deep infections that could compromise the healing process. Due to these concerns, orthoplasty has emerged as a widely accepted technique [1].

A modern approach to orthoplasty integrates both bony intervention and soft tissue closure techniques. The main components of orthoplasty include fracture fixation using either an external or internal fixator, combined with a concomitant flap procedure (either free or local). However, the technical demands and extended surgical time pose significant challenges, particularly for polytrauma patients who require shorter operative durations due to their systemic burden. To address these limitations, trauma surgeons have developed innovative methods using external fixators. These methods primarily involve a combination of fracture fixation and soft tissue tension release through acute shortening or angulation, facilitating wound closure [2–7].

Devices such as monolateral external fixator, Ilizarov circular external fixator, and spatial frames have all been described in relation to their specific applications. The described techniques include acute angulation of the fracture site followed by gradual correction, acute shortening with subsequent lengthening at the fracture site, and osteotomy at a different location with gradual lengthening. The key advantages of these procedures include the avoidance of internal hardware, which reduces the risk of infection in exposed bone, and the ability to perform soft tissue interventions independently of bony procedures in cases where soft tissue healing fails. Additionally, these techniques allow for minor system adjustments to achieve an acceptable reduction. Furthermore, relieving soft tissue tension has been identified as an effective method to promote healing and induce flap hypertrophy, a process also referred to as gradual expansion muscle flap, which involves acute shortening and angulation of the tibia, rotational muscle flap coverage, and split-thickness skin grafting of the soft tissue defect [6]. Distraction osteogenesis for restoring limb length enhances blood perfusion in the affected extremity, which may also facilitate soft tissue healing, promote fracture union, and reduce the risk of infection [8, 9].

Open fractures may lead to contamination of the fracture site and injury to adjacent neurovascular structures. Although external fixator-guided soft tissue coverage has been reported to achieve high healing rates, certain concerns remain, particularly regarding vascular disturbances in the affected extremity, which may result in complications such as lymphedema, necrosis, and swelling [10]. Although no consensus exists in the literature regarding the safe range of acute shortening, some authors have suggested an acute shortening of up to 3 cm for acute intervention, recommending gradual shortening for larger defects to prevent arterial flow obstruction [2]. Similarly, no objective data define the degree and related direction of acute angulation that may lead to arterial obstruction [5]. Furthermore, additional artificial shortening during wound closure may complicate the establishment of standardized angular measurements for these procedures.

In this cadaveric study, we aimed to simulate acute angulation in all directions at both the proximal tibia and distal femur, documenting macroscopic arterial diameter changes and determining the critical angles.

Materials and methods

Ethical approval for the study was obtained from the local ethics committee. The study included eight lower extremities from four fresh-frozen cadavers. Osteotomies were performed at the distal femoral and proximal tibial metaphyses, selected due to the close proximity of adjacent arteries to the bone. The distal femoral metaphyseal osteotomy corresponds to the region of the adductor canal, whereas the proximal tibial osteotomy was performed distal to the trifurcation of the popliteal artery, where vascular assessment was conducted at the level of the posterior tibial artery.

To standardize the osteotomy, an Ilizarov frame consisting of two circular rings and two hinges which are aligned perpendicularly to the desired axis of angulation was used. The frame was secured proximally and distally at the planned osteotomy site with two Schanz screws on each side. To prevent unintended changes in bone length, a Kirschner wire-guided dome osteotomy was performed, and 2.5 cm of the fibula was excised in the tibia group (Fig. 1).

In our study, the iodinated contrast agent iohexol (Omnipaque®) was used for vascular visualization. The contrast medium was administered intra-arterially via the proximal femoral artery, ensuring continuous injection under fluoroscopic guidance. The infusion was continued until the vessel assumed a completely straight configuration, indicating the elimination of tortuosity. At this point, the injection was ceased, and the proximal segment of the artery was clamped to maintain the contrast-filled state for optimal imaging and analysis (Fig. 1). This approach allowed for precise assessment of arterial morphology and changes in vascular diameter under varying angulation conditions.

Since arterial narrowing is a well-known risk factor for turbulent flow and thrombus formation, as demonstrated in physiological studies on blood flow, the angle at which

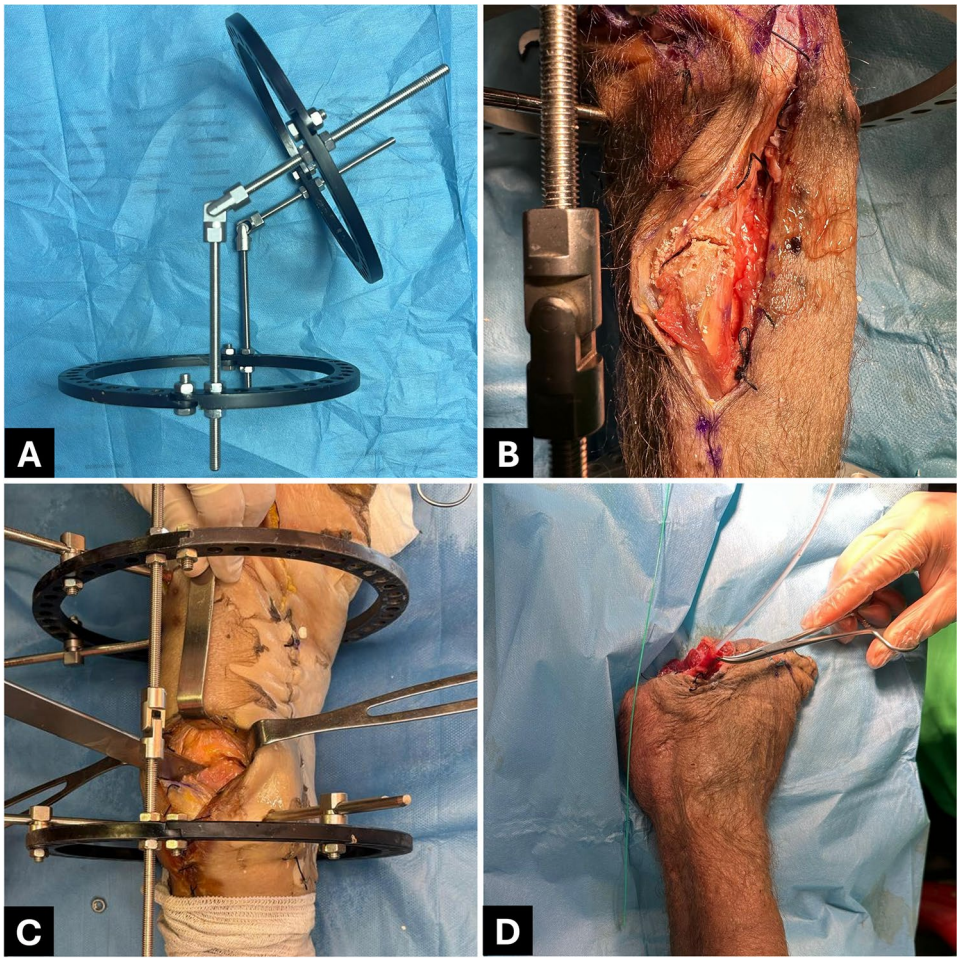


Fig. 1 Pre-procedural setup of a double-ring Ilizarov external fixator with a single hinge in place (**A**). Completed dome osteotomy (**B**). Dome osteotomy with an Ilizarov external fixator attached to the bone (**C**). A catheter inserted into the proximal femoral artery for contrast administration (**D**)

the artery became constricted was identified as the critical threshold posing a risk to arterial flow [11].

Frame Preparation

Two circular rings were connected by two hinges vertically aligned with the angulation axis that had been prepared before the procedure. To prevent translation or unintended deformities, fixation was achieved using two Schanz screws placed in different planes. Since coronal and sagittal plane angulations required distinct vertical configurations, the hinge positions were adjusted accordingly after the initial angulation procedure. All angulations were performed manually (Fig. 1).

Surgery

An anterior incision was made over the osteotomy site. After positioning retractors medially and laterally, a 2.5 mm Kirschner wire was used to drill a dome-shaped pattern in the proximal tibia and distal femur in different sessions. Then, an osteotome was used to unite the wire holes. The completion of the osteotomy was confirmed under fluoroscopy. The femoral artery was dissected through the femoral triangle in the proximal part of the extremity. After identifying the Sartorius and adductor muscles, the vascular bundle was located, and the artery was exposed. An embolectomy catheter was used to assess the integrity of the artery and to check for any obstruction along its course. In all the cadavers, the catheter was successfully advanced to the middle of the crura. After arterial dilation, the feeding catheter was sent through the artery, and the artery was filled with radiopaque contrast material (Fig. 1). Fluoroscopy was used for precise visualization of the artery.

Angulations

After the osteotomy and administration of the radiopaque material, the osteotomy site was angulated in both varus and valgus directions. Real-time fluoroscopic imaging during continuous angulation of the osteotomy site was performed until the narrowing of the adjacent artery was observed. Upon detection of narrowing, a plastic goniometer was positioned at the hinge center

and precisely aligned to measure the angulation (Figs. 2 and 3). This procedure was repeated three times, and the smallest of the measured angles was considered the safe angular limit for the deformity. After realigning the bone, the hinges were repositioned medially and laterally to repeat the procedure in the anterior and posterior directions. Angle measurements were conducted in the same manner as in the coronal plane.

Statistical analysis

Statistical analyses were conducted using Python (SciPy and pandas). Descriptive statistics, including means and standard deviations, were calculated for each angulation type. Normality was assessed using the Shapiro-Wilk test. Since most data did not meet normality assumptions, Mann-Whitney U tests were used to compare angulation thresholds between the femur and tibia, with a significance level of $p < 0.05$. Effect sizes were calculated using Cliff's Delta, categorized as negligible (< 0.147), small (0.147–0.33), medium (0.33–0.474), or large (> 0.474), with large values indicating meaningful differences.

Results

The angulation measurements at which arterial narrowing occurred are presented in Table 1. For the proximal tibia, the mean varus and valgus angulations were 45.5° (30–58°) and 26.5° (24–30°), respectively, while the procurvatum and recurvatum angulations measured 33.8° (32–36°) and 13.5° (12–15°). In the distal femur, the mean varus and valgus angles were 27° (24–29°) and 32.3° (21–46°), whereas the procurvatum and recurvatum angles were 52° (40–62°) and 22° (18–29°), respectively.

Angulations in the coronal plane were better tolerated in terms of mechanical control. Recurvatum angulation led to arterial narrowing at smaller angles than procurvatum. In the proximal tibia, arterial narrowing occurred at similar angles for both varus and valgus angulations, demonstrating consistency in their effects on vascular flow. Similarly, distal femur angulations showed comparable osteotomy effects on the femoral artery. However, varus deformities were better tolerated than valgus deformities, as arterial narrowing occurred at smaller valgus angles compared to varus.

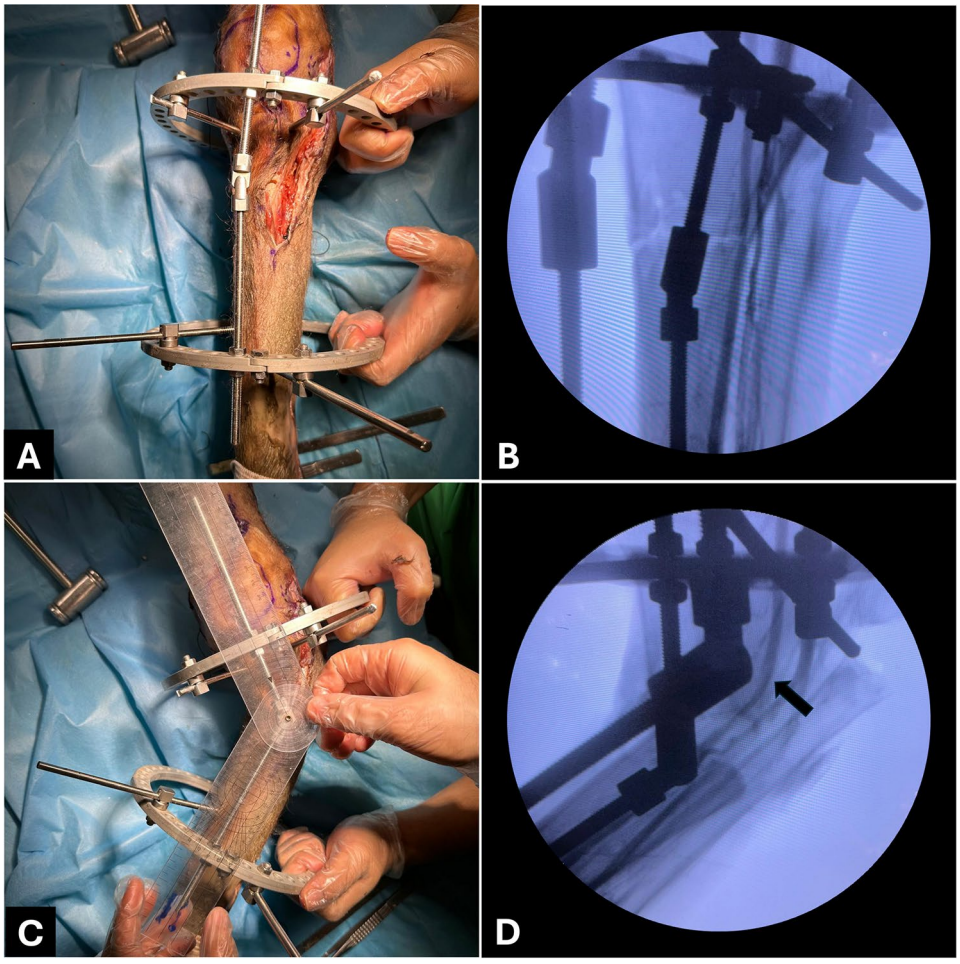


Fig. 2 Clinical (**A**) and fluoroscopic (**B**) images of the tibia in a neutral position after contrast administration. Clinical image of the tibia in a varus position with a goniometer for angle measurement (**C**), and the corresponding fluoroscopic image with an arrow indicating arterial narrowing (**D**)

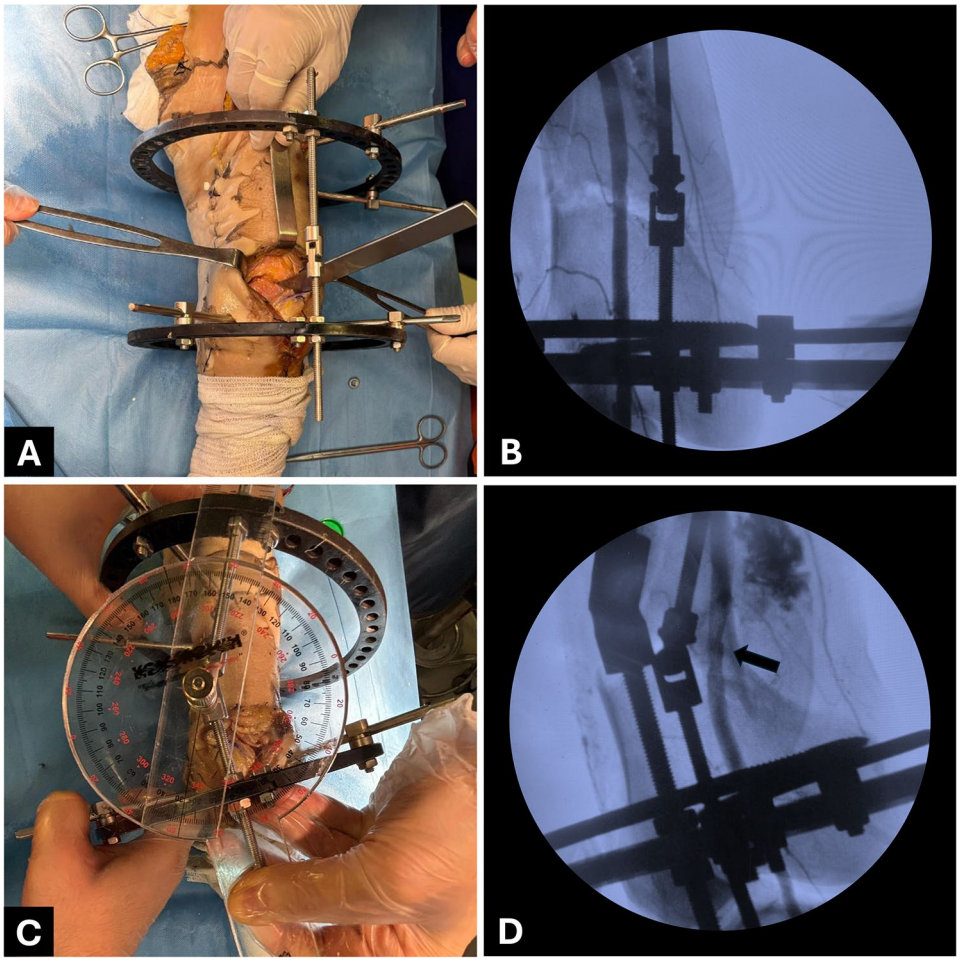


Fig. 3 Clinical (**A**) and fluoroscopic (**B**) images of the femur in a neutral position after contrast administration. Clinical image of the femur in a varus position with a goniometer for angle measurement (**C**), and corresponding fluoroscopic image with an arrow indicating arterial narrowing (**D**)

Table 1 Angular measurements of the proximal tibia and distal femur when arterial narrowing occurs

Osteotomy Site	Sample	Varus	Valgus	Procurvatum	Recurvatum
Proximal tibia	Tibia 1	58	24	32	12
	Tibia 2	46	30	36	14
	Tibia 3	30	24	35	15
	Tibia 4	48	28	32	13
Mean (± SD)		45.50 (± 11.59)	26.50 (± 3.00)	33.75 (± 2.06)	13.50 (± 1.29)
Distal femur	Femur 1	27	34	40	18
	Femur 2	28	46	62	21
	Femur 3	29	21	51	29
	Femur 4	24	28	55	20
Mean (± SD)		27.00 (± 2.16)	32.25 (± 10.59)	52.00 (± 9.20)	22.00 (± 4.83)
p-value		**0.029**	0.559	**0.029**	**0.029**
Cliff's delta value		-1.00	0.31	1.00	1.00

SD, standard deviation

The maximum varus angulation before arterial narrowing was significantly greater at the proximal tibial location ($p = 0.0286$), while procurvatum ($p = 0.0294$) and recurvatum ($p = 0.0286$) thresholds were higher at the distal femoral site. No significant difference was observed for valgus angulation ($p = 0.559$). Cliff's Delta analysis revealed large effect sizes for varus (-1.00), procurvatum (1.00), and recurvatum (1.00), indicating substantial practical differences between anatomical locations. In contrast, the effect size for valgus was small (0.31),

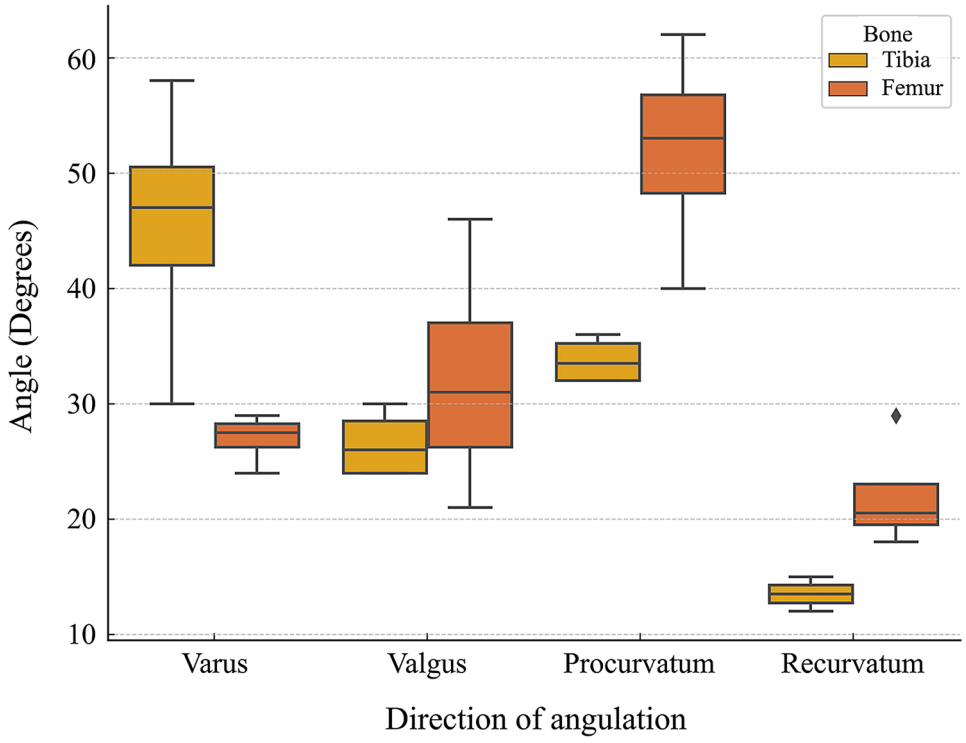


Fig. 4 Box plot illustrating the distribution of angulation thresholds in all directions for both the tibial and femoral sites at which arterial narrowing occurred

suggesting a negligible difference in safe angulation between the femur and tibia in this direction. Boxplot visualizations illustrate the distribution of safe angulation thresholds across all angulation types, highlighting the significant differences in varus, procurvatum, and recurvatum angulation thresholds (Fig. 4).

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Discussion

Shortening and angulation using an external fixator are effective and safe methods for managing open fractures that cannot be primarily closed. Although favorable outcomes have been reported in terms of soft tissue healing, no standardized guidelines exist to define the safe limits of angulation without increasing the risk of thrombus formation. This study aimed to evaluate the vascular implications of acute angulation in anatomical regions where arteries are in close proximity to the bone, providing insight into the risks of arterial narrowing and thrombus formation. It is well established that narrowing of vessels can induce turbulent blood flow, predisposing to thrombus formation. Therefore, the safe angulation threshold was defined as the angle at which arterial narrowing first occurred.

The maximum tolerable varus angulation before vascular narrowing was observed at 30° for the proximal tibia and 24° for the distal femur, while for valgus deformity, these values were 24° and 21°, respectively. Similarly, the maximum safe procurvatum angulation was 32° for the proximal tibia and 40° for the distal femur, whereas recurvatum deformities were limited to 12° and 18°, respectively.

The most striking findings of this study were, first, that varus angulation was more tolerable before vascular compromise occurred, and second, that procurvatum angulation was better tolerated than recurvatum angulation. These results should be considered when planning acute angulation and gradual correction in patients with open fractures with soft tissue defects or those undergoing acute correction of proximal tibial or distal femoral deformities. Furthermore, identifying these critical angulation thresholds may provide insight into vascular status, serving as a potential *red flag* during the initial evaluation of an angulated fracture and necessitating meticulous follow-up.

The significant differences observed in varus, procurvatum, and recurvatum suggest that tibial and femoral angulations impose distinct biomechanical limitations on arterial flow. Notably, varus angulation was better tolerated at the proximal tibia, whereas procurvatum and recurvatum were safer at the distal femur. The lack of significance in valgus angulation suggests that femoral and tibial structures may provide similar vascular protection in this direction. These findings indicate that tibial deformities require precise angulation control in procurvatum and recurvatum to avoid vascular compromise, while

femoral varus angulations should be evaluated carefully to ensure adequate arterial perfusion.

The treatment of bone defects with associated soft tissue loss is a complex and delicate process. The primary goals include achieving fracture healing, restoring normal extremity alignment, preventing infection, and reconstructing healthy soft tissue. Various external fixator modifications, such as acute or gradual angulation and shortening, have been developed to achieve these objectives. Although these techniques are generally considered safe, certain limitations, such as pre-existing scar tissue, venous stasis, and lymphedema, can present challenges and restrict their application.

The safe threshold for acute shortening before vascular complications has been well-documented. In a clinical study involving 16 patients, the authors performed acute shortening and assessed resulting structural changes using angiography. Their findings indicated that 4 cm of shortening was safe, with minimal arterial bending observed between 4 and 6 cm, while shortening beyond 8 cm resulted in significant vascular tortuosity [10]. However, post-surgical vascular assessment using Doppler ultrasound was strongly recommended. While significant data exist regarding the effects of shortening, no objective guidelines have been established for safe angulation techniques to the best of our knowledge.

The gradual expansion muscle flap technique was introduced as a method that combines intentional deformity using an external fixator, with concurrent local muscle flap coverage of open fracture fragments, and gradual deformity correction following wound healing. Circular and spatial fixators have been successfully used for this approach. In a clinical study defining gradual muscle expansion flap as a novel surgical technique, quantitative measurements of intentional acute angulation were reported. The mean values for artificial deformities were 30.4° of varus and 20.6° of recurvatum. Although these values were identified as reference points, the study emphasized that an additional 5.3 cm of shortening was required for the patients [12].

Another systematic review on acute shortening highlighted the lack of standardized criteria for determining the appropriate degree of shortening, angulation, rotation, and soft tissue defect size [5]. One of the largest series on intentional deformity creation reported favorable outcomes, with a mean applied varus angulation of 15.3° ± 10.2°, a valgus angulation of 5.6° ± 3.8°, and a shortening of 2.8 ± 1.4 cm [13]. These values were established as the required parameters for soft tissue defect closure. The authors emphasized that the vascular status of patients was continuously monitored during surgery, and any induced deformity was reversed if vascular deterioration was observed. Therefore, these values should not be interpreted as absolute safety limits but rather as values that have been clinically validated as safe. A case series involving three patients documented the use of this technique. The first patient underwent 30° angulation with 4 cm of necrotic bone resection, the second had 20° anterior angulation with 3 cm resection, and the third underwent 45° valgus angulation with 5 cm cortical defect [4]. All patients achieved excellent outcomes without any vascular complications.

Popliteal artery thrombosis has been reported following total knee arthroplasty, often linked to tourniquet use and flexion contracture corrections [14]. Similarly, femoral artery thrombosis has been observed after femoral fractures, and popliteal artery thrombosis following proximal tibial epiphyseal fractures, highlighting the impact of mechanical stress on vascular injury [15, 16]. Arterial thrombosis associated with orthopedic fractures and deformities is primarily linked to intimal injury and direct arterial trauma. Previous studies on carotid and hepatic artery kinking suggest that angulation alone can impair blood flow, leading to thrombus formation [17, 18]. These findings further support the need for defining safe angulation limits in orthopedic applications.

To the best of our knowledge, this is the first experimental study to evaluate the relationship between acute angulation and the resulting mechanical stress on the adjacent artery. While most clinical studies support fixator-assisted management of open fractures with soft tissue defects, they often involve additional shortening, which may have influenced the determination of standard angulation thresholds in previous research. To overcome this issue, we performed a dome osteotomy to maintain limb length and eliminate the confounding effects of shortening. An Ilizarov circular external fixator was used to allow precise angle measurement at the hinge and to prevent unintended translation during the angulation process.

Although this study provided valuable findings, it had certain limitations. The relatively small sample size may have affected the statistical power of the findings, despite the use of non-parametric tests and effect size analyses to mitigate this issue. Future studies with larger sample sizes are needed to confirm these results. As a cadaveric study, individual vascular factors such as age, atherosclerosis, and anatomical variability could not be assessed, which may limit the generalizability of the angulation thresholds to clinical settings. Additionally, the radiopaque material was administered manually, leading to a lack of methodological standardization. Another limitation was that deformities were created only around the knee joint, whereas most clinical studies focus on the diaphysis or distal tibia. This limitation may reduce the generalizability of our findings to other clinical scenarios. However, by selecting anatomical locations where vascular mobility is most restricted, we ensured that the observed vascular

responses were primarily due to angulation, effectively minimizing potential confounding factors.

Conclusion

Varus and procurvatum angulations were found to be more tolerable and reliable for creating artificial deformities and facilitating treatment around the knee joint. In contrast, valgus and recurvatum deformities should be approached with greater caution when necessary. This study further highlights the anatomical differences in safe angulation thresholds and underscores the importance of considering bone-specific angulation risks in orthopedic procedures to optimize patient safety and treatment outcomes.

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Author contributions
AM, HCO, and BE performed the surgical procedures. AM, KAD, and BK conducted the initial literature review and conceptual groundwork. AM, MB, and MAD designed the experimental setup. KAD performed the statistical analysis. AM, KAD, and BK drafted the original manuscript. MB and MAD critically reviewed and edited the manuscript. MAD and MB provided overall supervision and guidance throughout the project. All authors read and approved the final manuscript.

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Data availability
The study data will be available upon request to the corresponding author.

Declarations

Ethics approval and consent to participate
Ethical approval for the study was obtained from the Ethics Committee of Çukurova University Faculty of Medicine with decision number 39, taken at meeting number 151 on January 3, 2025.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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