REVIEW ARTICLE

Hexapod Circular Frame Fixation for Tibial Non-union: A Systematic Review of Clinical and Radiological Outcomes

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Abstract

Introduction: Tibial non-unions present with complex deformities, bone loss, infection, leg length discrepancy (LLD), and other features which influence function. Circular frame-based treatment is popular with the hexapod system used increasingly. This systematic review aims to determine the clinical and radiological outcomes of hexapod fixation when used for tibial non-unions.

Materials and methods: The review was performed in accordance with preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines. The search strategy was applied to MEDLINE and Embase databases on 15 December 2021. Studies reporting either clinical or radiological outcomes following hexapod fixation on tibial non-unions were included. Primary outcomes were radiological union and patient-reported outcome measures (PROMs). Secondary outcomes included LLD, tibial alignment deformity (TAD), return to pre-injury activity and post-operative complications.

Results: After the abstract and full-text screening, 9 studies were included; there were 283 hexapod frame fixations for tibial non-unions. Infection (46.6%) and stiff hypertrophic non-union (39.2%) accounted for most non-unions treated. The average age and mean follow-up were 42.2 years and 33.1 months, respectively. The average time to union was 8.7 months with a union rate of 84.8%. A total of 90.3% of patients had TAD below 5° in all planes, with an LLD ≤1.5 cm of the contralateral leg in 90.5%. Bony and functional results were at least good in over 90% of patients when using the Association for the Study of the Method of Ilizarov (ASAMI) criteria. A total of 84% of patients returned to pre-injury activities. There were complications as follows: a total of 34% developed pin-site infection, almost 9% experienced half-pin breakage and 14% developed an equinus ankle contracture.

Conclusion: Hexapod frames for the treatment of tibial non-unions produce favourable functional outcomes. Complication rates are present and need to be discussed when this modality of treatment is proposed. Further comparative studies will allow for this option to be evaluated against that of the traditional Ilizarov frame and other methods of non-union surgery.

Keywords: Deformity Correction, Functional outcomes hexapod, Non-union, Union.

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Introduction

Tibial non-union, following a fracture, can range between 2.5 and 17.5% owing to its anatomical location and soft-tissue coverage.[1,2] Non-union can be classified as hypertrophic or atrophic, stiff or mobile, with or without bone defects and the presence or absence of infection.[3,4] Such diversity underlines the range of different treatment strategies and why there currently is no standardised method for its management.[5,6] However, a recent treatment algorithm for the use of circular frames in distraction, deformity correction, stabilisation and bone transport based on the type of tibial non-union has been proposed.[7] Although the Ilizarov method has many advocates over the last three decades for hypertrophic non-union,[8–11] and non-unions associated with bone defect and infection,[12–16] there are limitations in its use. Despite allowing for simultaneous distraction and compression, it has significant learning curves with frequent modifications,[12,13,17] need for multiple sequential corrections for angulation, translation and rotational deformities,[9,11,18,19] and a protracted time in frame with concerns of pin-site infection.[20,21] Such factors contribute to its increased costs.[22,23] Hexapod frames are a modification of the Ilizarov-type fixators.[24] Whilst applying the Ilizarov principles of distraction osteogenesis,[25] they use specialised struts and computer programme to calculate the position of a virtual hinge to simultaneously correct the multiplanar deformities without altering the frame construct during treatment.[18,26–28] Thus, compared to the Ilizarov method, they have a higher degree of precision for deformity correction and lower limb mechanical axis re-alignment, and a clear advantage in multidimensional deformity corrections.[27,29] This is particularly useful for tibial non-unions frequently presenting with complex deformities, bone loss, infection and LLD, factors which can affect the union.[30]

In view of this, we performed a systematic review of the literature to investigate the clinical and radiological outcomes of hexapod frames on tibial non-unions.

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Materials and Methods

Literature Search

A systematic review of the literature was conducted in accordance with the PRISMA guidelines,[31] using the online databases MEDLINE and Embase. This was conducted from the inception of the databases to 15 December 2021. The full search strategy can be found in Appendix 1. No restriction was made on language with efforts made to obtain the translated-to-English versions of all included studies. Bibliographies of included studies were examined for missed and potentially relevant studies.

Eligibility Criteria

All titles and abstracts returned by the search strategy were screened to identify studies reporting on clinical and radiological outcomes of hexapod frames on tibial non-unions. The main outcomes were as follows: (a) Clinical and radiological union and time to union; (b) TAD; (c) LLD; (d) function including a return to pre-injury work activity; and (e) post-surgical complications, namely, pin-site infection, component breakage, equinus contracture, LLD >1.5 cm and regenerate site deformity. Exclusion criteria were paediatric population, non-human studies, case reports or expert opinions, foreign papers not translatable to English and those involving intra-articular regions.

Study Selection and the Assessment of Quality

Two authors (KB and SK) independently reviewed the titles and abstracts, after which the relevant papers were reviewed in full by each author. Those that met the eligibility criteria were chosen with any discrepancies reviewed by a third author (AA). The same two authors independently assessed the quality of studies using the modified Coleman methodology score (MCMS) adjusted to account for the subject matter (Table 1).[32] The MCMS is based on a scale ranging 0–100; scores of 85–100 are considered excellent, 70–84 are considered good, 55–69 are considered fair, and scores below 55 are considered poor.[32] Any discrepancy of more than 4 points between both reviewers was highlighted and resolved by the senior author (AA).

Results

A total of 216 abstracts were identified from the initial search. Application of the eligibility criteria resulted in the inclusion of 9 studies.[25,33–40] This is summarised in Flowchart 1. After full data extraction, we recognised there was insufficient data to undertake a meta-analysis. We, therefore, proceeded to do a qualitative synthesis of the data.

Methodological Quality of Included Studies

Regarding MCMS of the 9 studies (mean score: 59.7), 6 achieved fair scores,[33–36,38,39] and 3 poor scores.[25,37,40] The overall quality of the studies was fair. Baseline characteristics are provided in Table 2.

In total there were 283 hexapod frame fixations for tibial non-unions. The average age and mean follow-ups were 42.2 years and 33.1 months, respectively. Common methods of fracture stabilisation before limb salvage with hexapod fixation were monolateral external fixators (25.4%), plate osteosynthesis (24.3%) and intramedullary nailing (19.8%). The average number of surgeries before hexapod fixation was 2.6. The Taylor spatial frame (TSF) (Smith and Nephew, Inc, Memphis, Tennessee) was the predominant hexapod used (77.4%), with 9.2% of patients treated with the TrueLock-Hex (TL-HEX) (Orthofix, Verona, Italy) and the remainder unknown.[33] Stiff hypertrophic non-unions (39.2%) and infected non-unions (46.6%) accounted for most cases treated with the hexapod, with the former undergoing closed distraction or deformity correction or both, and the latter bone transport. Furthermore, the closed distraction was predominantly monofocal.[35–38] Bifocal osteogenesis was generally performed for bone transport,[25,33,34] with trifocal performed for larger defects.[39] There were 40.7% of patients who were smokers at the time of hexapod fixation.

Radiological Outcomes (Table 3)

The average time to union was 8.7 months. Subgroup analysis revealed those with infected non-unions united at 10.6 months,[25,33,34,40] compared to 5.8 and 5.6 months in those without infection and with stiff hypertrophic non-unions, respectively.[25,35,37,40] There was union in 84.8% of all cases after hexapod fixation, with 97.1% uniting after adjuvant stability was introduced. The remaining 6 patients either had an amputation (four cases)[25,37,38] or withdrew from treatment,[36] or were erroneously treated with closed distraction.[35] Subgroup analysis revealed 6 studies that specifically gave union rates for infected non-unions. A reported 100% union was achieved in four studies.[36,38–40] One study revealed infection to be an independent risk factor for non-union.[25] The final study showed union in 55.2% of cases but did not record results after adjuvant stabilisation.[33] Three studies reported on union rates for stiff hypertrophic non-union: 100% union was achieved in one,[40] with a 98% union from 87% after adjuvant stability in the other two.[35,37]

Absence of malalignment was recorded in 90.3% of patients where a TAD of <5° in all planes and an LLD ≤1.5cm to the contralateral leg in 90.5%.[25,34–39] Only one study compared LLD before and after hexapod application, with over 1-cm improvement in deformity.[25]

Clinical Outcomes (Table 4)

The ASAMI scores revealed bony and functional results to be at least good in 94.2 and 90% of patients, respectively.[25,34,38,39] The 12-item short-form health survey (SF-12) in two studies revealed the patient's physical and mental scores to be within the norm of the US population mean score (50).[37,40] One study used the short musculoskeletal functional assessment (sMFA) tool and found worse function after hexapod application compared to the standard population (27.1 vs 12.7, $p < 0.0001$).[33] There were 84.2% of patients who were able to return to pre-injury activities.[34,38,40] Subgroup analysis revealed smokers had slightly worse SF-12 physical scores (47.89 ± 14.13 vs 50.09 ± 7.00)[37] and sMFA scores (39 ± 16 vs 22 ± 14, $p = 0.011$).[33]

Complications (Table 5)

Six studies reported on pin-site infection,[34,35,37–40] although one presented its overall data to include Ilizarov frames.[39] After exclusion, 34.3% of patients developed a pin-site infection following hexapod fixation for tibial non-unions. The same six studies reported half-pin breakage in 8.8% of all cases. Two studies commented on the development of equinus contractures in 14.3%.[34,39] These patients had trifocal bone transport and underwent successful treatment with Achilles tendon lengthening with frame extension to the foot. There were 9.5% of patients who had LLD above 1.5 cm and were treated with a shoe lift. Three studies reported on regenerate site bending, with above

Table 1: Modified Coleman's criteria used for assessment of the quality of studies

Criteria		
Part A		
Study size (total patients)	>40	15
	25–40	10
	11–24	5
	<10	0
Mean follow-up (months)	>24	10
	12–24	5
	<12, not stated or unclear	0
Type of study (methodology)	Randomised controlled trial	12
	Prospective cohort study	7
	Prospective/retrospective mixed	3
	Retrospective cohort study	0
Diagnostic certainty (confirmed non-union)	In all	5
	>80%	3
	<80%	0
Part B		
Outcome criteria (15)	Clearly defined outcome	3
	Timing of outcome assessment clearly stated	3
	PROMs used	3
	Radiological assessment	3
	Other clinical/functional outcomes measured (other than PROMs)	3
Procedures for assessing outcomes (6)	Clearly defined	2
	Objective	2
	Multiple/independent observers	2
Description of subject population (10)	Inclusion criteria reported and unbiased	4
	Recruitment rate reported >80%	3
	Recruitment rate reported <80%	2
	Recruitment rate not reported	0
	All eligible subjects accounted for in methodology	3
Surgical technique (6)	Method of bone transport	2
	Ilizarov principles adequately described	2
	Intraoperative techniques adequately described	2
	Removal of frame justified	2
Post-operative rehabilitation (6)	Well described	6
	Inadequately described	3
	Protocol not reported	0
Complications recorded (8)	All with explanations	8
	Selected complications recorded	4
	Incomplete record	2
	None	0
Adjuvant stability (5)	Time to adjuvant	3
	Stabilisation method	2
	Nil adjuvant	3

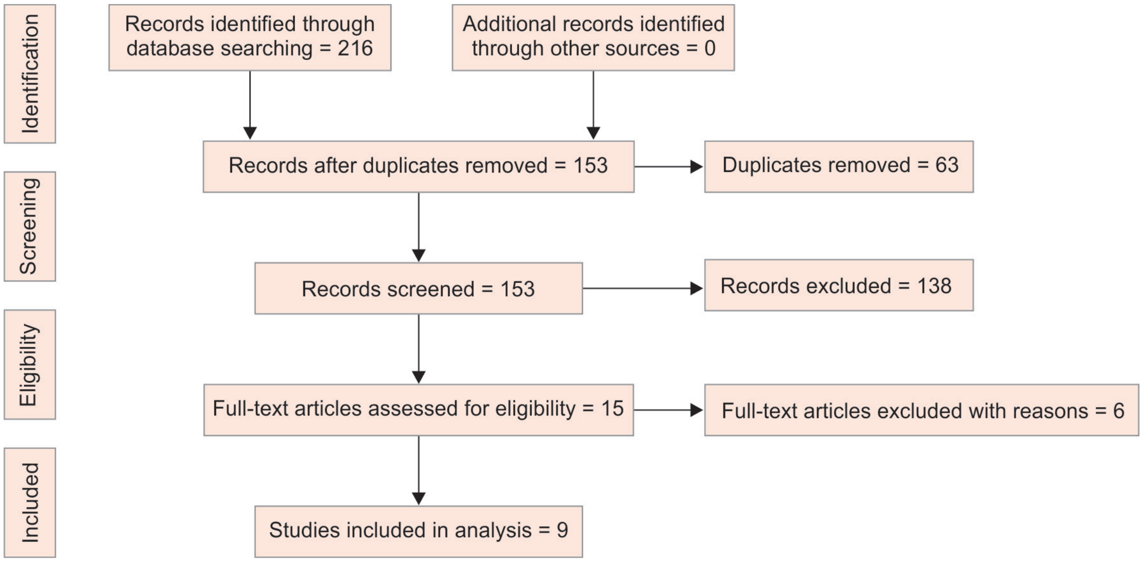
5° occurring in 5.7% of cases.[34,38,39] All were successfully treated with secondary correction.

Discussion

Management of tibial non-unions can be challenging. The hexapod system incorporates the Ilizarov technique of translating controlled axial micromovements into a biomechanical environment conducive to bone healing and regenerate formation.[26] In addition, they have a much higher degree of precision for deformity correction.[27,29] By adjusting the length of the six connecting struts, deformity correction can be achieved simultaneously with bone transport, and whilst restoring limb length discrepancy, eradicating infection, achieving union and soft-tissue coverage. This restores a functional limb and limits further complications.[12,14]

Our systematic review confirms the effective management of tibial non-unions with the hexapod frame. It reliably promotes

Flowchart 1: Preferred reporting items for systematic reviews and meta-analyses flowchart



union whilst accurately correcting concurrent deformities and limb-length discrepancies.

Patients with infected non-unions took 4.8 months longer to unite than those without, with Rozbruch et al. showing infection itself to be a risk factor for non-union.[25] This can be explained as follows: first, bone transport using the hexapod system was undertaken in the majority of these cases due to significant bone defects following debridement and grafting. Bone transport is inherently more complicated than compression distraction, with respectively longer treatment times and further operative procedures necessary. Additionally, a time delay exists before bony contact and compression at the docking site, which adds to treatment time.[13] A second reason is that, with any infected case, time to union is generally longer and more difficult.[15] Third, there are potential confounding factors for which the duration of hexapod fixation may depend on, for example, the patient's immune status, comorbidities, and type and chronicity of the infection.

The restoration of LLD within 1.5 cm (90.5%) and TAD <5° in all planes (90.3%) underlines the simplicity of using a hexapod and easier control of bony re-positioning than when using a traditional Ilizarov frame. This ease of use is cited by other authors as advantage of the system.[41,42] Five degrees of TAD in the sagittal (apex posterior or anterior angulation) or coronal (varus or valgus) was the value chosen in all included studies as acceptable for a normal mechanical axis.[43] Any significant alterations may increase the joint reaction forces leading to potential progression in knee and ankle osteoarthritis.[43] However, full correction of tibial alignment and LLD was not achieved in some studies.[25,34,35,37]

Although PROMs were generally favourable, Napora et al. showed worse mean sMFA scores than the uninjured reference population (27.1 vs 12.7, p< 0.0001).[33] The context to consider is the residual dysfunction that may remain for most of these patients following such complex musculoskeletal injury. There were improved sMFA scores at 8 years (19.4 at 98.8 months vs 27.1 at 59 months), suggesting that over time these patients approach levels of that of the normal population. Interestingly, univariate analysis of smoking in this study and that by Mahomed et al.[37] showed worse sMFA and SF-12 scores at the final follow-up respectively. This may suggest that links to delayed healing, higher non-union rates, and altered biomechanical properties of bone with nicotine exposure.[44] These findings are consistent with a previous study.[45]

Complication rates may be considered reasonable owing to the complex patient population, with pin-site infection rates similar to established series of frame management of tibial defects and deformity.[13] All cases responded to treatment with oral antibiotics, except for three in which two required wire re-positioning[34,38] and one required debridement, irrigation and hexapod re-application following deep infection.[40] Equinus contractures at the ankle are common complications during tibial lengthening and bone transport, particularly in trifocal transport, as underlined in the two included studies.[34,39] Despite successful treatment with Achilles tendon lengthening and frame extension to the foot, such complications can be prevented in the future through incorporating the foot in fixation for lengthening of more than 10%.[46]

Limitations

A meta-analysis was not conducted owing to the heterogeneity of the methods, the limited quality of several studies (three studies were of poor quality) and small sample sizes. The latter is understandable due to the scarcity and complexity of the patient population. A further limitation includes most of the studies performed at centres specialising in limb reconstruction, thereby limiting its external validity. Therefore, the results reported may be difficult to replicate in less experienced trauma units. However, treatment of tibial non-unions requires experience and specialised knowledge to achieve satisfactory outcomes.

Conclusion

This systematic review suggests hexapod frames are reliable for treating tibial non-unions with favourable outcomes. Future comparative studies should be undertaken to prove its efficacy over that of the Ilizarov frame.

Table 2: Baseline characteristics of included studies

Study	Study design	Study participants	Gender: Male	Gender: Female	Mean age ± SD (range)	Initial fracture: Closed vs open (%)	Initial surgery before hexapod: Type of surgery	Initial surgery before hexapod: Average number of surgeries	Hexapod: TSF	Hexapod: TL-HEX	Hexapod: Other
Napora et al.[33]	Retrospective cohort	38	28	10	46.8 ± 12.7	Not described	Not described	Not described	–	–	38
Sala et al.[34]	Retrospective case	12	8	4	44 (19–79)	0 vs 12 (100)	PO: 3, IM nail 2, Ex-fix: 7	3	12	–	–
Ferreira et al.[35]	Prospective	44 (46 frames)	31	13	35 (18–68)	10 (21.7) vs 36 (78.3)	Cast: 9, IM nail: 1 Unknown: 36	Not described	24	22	–
Rozbruch et al.[25]	Retrospective case	38	30	8	43 (8–72)	10 (26.3) vs 26 (68.4) 2 bone defects	PO: 9, IM nail:10, Ex-fix 19	4	38	–	–
Arvesen et al.[36]	Retrospective case	34 (37 frames)	26	11	49.7 (29–71)	7 (18.9) vs 30 (81.9)	PO, IM nail and Ex-fix	Not described	37	–	–
Mahomed et al.[37]	Retrospective case	32 (33 frames)	24	8	44 (18–80)	Not described	Cast: 7, PO: 7, IM nail: 10, Ex-fix: 8	Not described	29	4	–
Khunda et al.[38]	Retrospective case	40	28	12	39.5 (9–69)	16 (40) vs 24 (60)	Cast: 2, PO: 15, IM nail: 12, Ex-fix: 11	2	40	–	–
Aboumira et al.[39]	Retrospective cohort	55 (30 with TSF)	25	5	39 ± 20.4 (15–79)	Not described	Not described	Not described	30	–	–
Molepo et al.[40]	Retrospective case	9	7	2	38 ± 13	Not described	PO: 9	1	9	–	–

Study	Non-union: Type	Non-union: Tibial site	Non-union: Treatment	Non-union: Risk factor: Smoking [n, (%)]	Non-union: Risk factor: Diabetes [n, (%)]	Method of distraction osteogenesis	Mean size of defect (cm)	Mean external fixator index (months/cm)	Mean follow-up (months)
Napora et al.[33]	Infection	Not described	Bone transport	11 (29)	3 (8)	Bifocal	5.1 ± 1.6	1.9 ± 0.06	59
Sala et al.[34]	Infection	Proximal: 2 Middle: 4 Distal: 6	Bone transport	–	–	Bifocal: 6 Trifocal: 6	–	2.0 ± 0.9 (Bi: 2.63, Tri 1.31)	24 ± 4.7
Ferreira et al.[35]	Stiff hypertrophic	Not described	Closed distraction and deformity correction	19 (43.2)	1 (2.3)	Monofocal: 46	–	–	12 (6–40)
Rozbruch et al.[25]	Hypertrophic: 6 Atrophic 18 Normotrophic 14 Infected: 19	Proximal: 6 Middle: 12 Distal: 20	Hypertrophic: Closed distraction Atrophic: Mechanical align-ment, bone graft, compression Infected: Bone transport	10 (26.3)	4 (10.5)	Bifocal 17 Trifocal: 3 Unknown in rest	6.5 (1–16)	–	37 (15–63)
Arvesen et al.[36]	Hypertrophic: 24 Atrophic: 9 Normotrophic: 4 Infection 21	Distal: 37	Hypertrophic: Closed distraction Atrophic: Mechanical alignment, bone graft, compression Infected: Bone transport	20 (54.1)	2 (5.4)	Predominantly monofocal Bifocal if degenerate deficient	–	–	25.1
Mahomed et al.[37]	Stiff hypertrophic	Proximal: 6 Middle: 6 Distal: 21	Closed distraction and deformity correction	20 (62.5)	10 (31.3)	Monofocal	–	–	Does not state

Khunda et al.[38]	Infection: 15 Unknown: 25	Not described	Not adequately described	12 (30)	–	Monofocal 25 Bifocal: 15	–		26 (3–70)
Aboumira et al.[39]	Infection: 20 Unknown: 10	Not described	Bone transport	–	–	Bifocal: 10 Trifocal: 20	7.6 ± 3.5 (3–15)	1.97 ± 0.7 (1.1–3.4)	48 ± 12.8
Molepo et al.[40]	Infection: 7 Hypertrophic: 2	Distal: 9	Bone transport Closed distraction and deformity correction	–	–	Not described	–	–	41.7 ± 28.3

Study	*Outcomes*	*Rehabilitation protocol*	*MCMS*			*Value*
			A	*B*	*Total*	
Napora et al.[33]	sMFA	Day 0: Weight-bearing as tolerated	35	29	64	Fair
Sala et al.[34]	Mechanical axis deviation, LLD, Radiological union, ASAMI, Return to work	Day 0: Isometric quadriceps and knee ROM exercise Day 2: PWB Dynamisation 2 weeks before frame removal Week 4–6 post-frame removal: PWB	20	43	63	Fair
Ferreira et al.[35]	TAD, LLD, Radiological union	Dynamise after consolidation FWB after this period	32	37	69	Fair
Rozbruch et al.[25]	TAD, LLD, Radiological union, SF-36, AAOS, ASAMI,	Not described	25	29	54	Poor
Arvesen et al.[36]	Deformity correction in 6 axes, Mechanical axis deviation, LLD, Radiological union	Day 0: weight-bearing as tolerated Dynamize after consolidation FWB 2–3/52 before frame removal	25	33	58	Fair
Mahomed et al.[37]	TAD, Angulation, LLD, Radiological union, SF-12 form,	Day 0: Weight-bear as tolerated with early ROM exercises	15	38	53	Poor
Khunda et al.[38]	ASAMI, Satisfaction score, Radiological union, Return to work	Not described	25	38	63	Fair
Aboumira et al.[39]	Radiological union, LLD, ASAMI	Day 0: Quadriceps isometric and Knee ROM exercises Day 2: PWB with crutches Dynamize 3 weeks before frame removal Week 4–6 post-frame removal: PWB Week 6 onwards post-frame: FWB	20	42	62	Fair
Molepo et al.[40]	SF-12, Foot function index, Radiological union, Return to work	Not described	15	36	51	Poor

AAOS, American Academy of Orthopaedic Surgeons; ASAMI, Association for the Study of the Method of Ilizarov Criteria; Ex-fix, external fixator; FWB, full weight bearing; IM, intra-medullary; PO, plate osteosynthesis; PWB, partial weight; ROM, range of motion; SF, short form health survey; TL-HEX, TrueLock hexapod; TSF, Taylor spatial frame; Tri-, trifocal, LLD, leg length discrepancy; sMFA, short musculoskeletal functional assessment

Table 3: Radiological outcome measures in hexapod fixation for tibial non-unions

Study	Ilizarov principles: Latency (days)	Ilizarov principles: Distraction rate (mm/day)	Ilizarov principles: Consolidation (days)	Mean time in frame/time to union (months ± SD)	Radiological – Lower limb axis measurements: mMPTA 87° (85–90)	aPPTA81° (77–84)	mLDTA89° (86–92)	aADTA80° (78–82)	TAD <5° in all planes[n, (%)]	Leg length alignment (≤1.5 cm of contralateral leg) (%)	Union: Post-hexapod Fixation (%)	Union: Adjuvant stability (%)
Napora et al.[33]	–	0.75 (NS) 0.5 (S)	–	9.3 ± 3.0	–	–	–	–	–	–	21 (55.2)	Unknown post-re-application of hexapod, IM nail or PO
Sala et al.[34]	12–14	0.5–1.0	–	13.9 ± 3.3 (Bifocal: 15.2 Trifocal: 12.6)	Pre: 90.2 Final: 87	Pre: 83.3 Final: 80.5	Pre: 92 Final: 88	Pre: 80.5 Final: 80.1	12 (100)	10 (83.3)	12 (100)	Not required
Ferreira et al.[35]	0	1.0	–	5.75 (2.75–12.25)	–	–	–	–	42 (91.3)	46 (100)	41 (89.1)	45 (97.8) post-re-application of hexapod in 4 that failed
Rozbruch et al.[25]	–	–	–	9.63 (3.97–23.83) Infection > No infection 11.47 ± 5.73 vs 7.2 ± 3.4, *p* 0.02)	–	–	–	–	32 (84.2)	Pre-frame vs post-frame 3.1 cm (1–5.7) vs 1.8 cm (0–6.8)	27 (71.1) Non-union: Infection > No infection [9/11 (81.1%) vs 2/11 (18.2%), $p = 0.03$]	36 (94.7) post-TSF re-application and ABG: 4, IM nail: 3, PO: 2 and amputation: 2
Arvesen et al.[36]	–	0.5–1.0	–	6.01 ± 3.56	36 (97.3%) corrected within 5°	–	25 (67.6%) corrected within 5°	–	37 (100)	36 (97.3)	32 (86.4)	35 (94%) post-TSF re-application: 3, TTC fusion: 1 Treatment refusal: 1
Mahomed et al.[37]	10	1.0	–	5.27	–	–	–	–	24 (72.7)	24 (72.7)	29 (87.9)	32 (97) post-ABG: 3 Amputation: 1
Khunda et al.[38]	–	–	–	10.5 (3–38.5)	–	–	–	–	–	–	39 (97.5)	Not required Amputation for pain: 1
Aboumira et al.[39]	12–14	0.5–1.5	56	13.9 ± 4.8 (5.6–25.7)	–	–	–	–	30 (100)	27/30 (90)	30 (100)	Not required
Molepo et al.[40]	–	–	–	7.76 ± 4.9 Infection > No infection 9.14 ± 5.16 vs 4.56 ± 2.37	–	–	–	–	–	–	9 (100)	Not required

ABG, autologous bone graft; IM, intra-medullary; PO, plate osteosynthesis; TSF, Taylor spatial frame; TTC, tibiotalocalcaneal fusion; aPPTA, anatomic posterior proximal tibial angle; NS, non-smoker; S, smoker; mLDTA, mechanical lateral distal tibial angle, aADTA, anatomic anterior distal tibial angle; mMPTA, mechanical medial proximal tibial angle

Table 4: The PROMs in hexapod fixation for tibial non-unionss

	PROMs								
		ASAMI			SF-12				
Study	*sMFA*	*Bone*	*Function*	*AAOS*	*Physical*	*Mental health*	*SF-36*	*FFI*	*Return to pre-injury activity (%)*
Napora et al.[33]	Control >Study (27.1 vs 12.7, $p < 0.0001$)			–	–	–	–	–	–
Sala et al.[34]		Excellent: 10, Good: 2	Excellent: 6, Good: 5 Fair: 1	–	–	–	–	–	12 (100)
Ferreira et al.[35]	–	–	-	–	–	–	–	–	–
Rozbruch et al.[25]	–	Excellent: 24, Good: 12, Poor: 2	Excellent: 20, Good: 14, Fair:2, Poor: 2	Pre-frame <Post-frame (56 vs 82, $p < 0.001$)	–	–	Post-frame > pre-frame (51 vs 19, $p = 0.001$)	–	–
Arvesen et al.[36]	–	–		–	–	–	–	–	–
Mahomed et al.[37]	–	–		–	Study ~ Control 47.84 ± 9.2 vs 50.0 ± 10, $p > 0.05$	Study ~ Control 58.05 ± 7.47 vs 50.0 ± 10, $p > 0.05$	–		–
Khunda et al.[38]	–	Excellent:33, Good:5, Fair: 1, Poor: 1	Excellent: 29, Good: 8 Fair: 2, Poor: 1	–	–		–	–	28/36 (77.8)
Aboumira et al.[39]	–	Excellent; 17, Good: 10 Fair: 2, Poor: 1	Excellent: 14, Good: 12 Fair: 3, Poor: 1	–	–		–	–	–
Molepo et al.[40]	–	–		–	Study ~ Control 49.4 ± 7.7 vs 50.0 ± 10, $p > 0.05$ 50.0 ± 10, $p > 0.05$	Study ~ Control 55.3 ± 8 vs 50.0 ± 10, $p > 0.05$	–	24.9 ± 18	8 (88.9)

AAOS, American Academy of Orthopaedic Surgeons; ASAMI, Association for the Study of the Method of Ilizarov criteria; SF, short form health survey, FFI, foot function index; sMFA, short musculoskeletal functional assessment

Table 5: Post-surgical complications following hexapod circular frame fixation for tibial non-union

	Post-surgical complications following hexapod fixation					
Study	*Pin-site infection (%)*	*Half-pin breakage (%)*	*Equinus ankle contracture (%)*	*LLD >1.5 cm(%)*	*Regenerate site bending (%)*	*Others (%)*
Napora et al.[33]	–	–	–	–	–	–
Sala et al.[34]	10 (83.3) Treatment: Local care 5, oral antibiotics 4, Wire re-tension 1	4 (33.3)	3 (25), All trifocal Treatment: AT lengthening with frame extension to foot	2 (16.7) Treatment: Shoe lift	< 5°: 3 (25) Nil treatment	Peroneal pseudoaneurysm:1 (8.3) Treatment: Embolisation
Ferreira et al.[35]	9 (19.5) Treatment: Local care and oral antibiotics	1 (2.2) Treatment: Replacement	–	0 (0)	–	–
Rozbruch et al.[25]	–	–	–	–	–	–
Arvesen et al.[36]	–	–	–	1 (2.7) Treatment: Shoe lift	–	–
Mahomed et al.[37]	5 (15.2) Treatment: Local care and oral antibiotics	2 (6.1) Treatment: Replacement	–	9 (27.2) Treatment: Shoe lift	–	–
Khunda et al.[38]	23 (57.5) Treatment: oral antibiotics 22, wire re-tension 1	1 (2.5) Treatment: Replacement	–	–	> 5 °: 2 (5) Treatment: Secondary correction	Knee flexion deformity: 1 (2.5) Treatment: Frame extension above knee
Aboumira et al.[39]	31/55 (56.3) Value for TSF in isolation unknown	5 (16.7) Treatment: Removal	3 (10), All trifocal Treatment: AT lengthening with frame extension to foot	3 (10) Treatment: Shoe lift	< 5°: 3 (10) >5°: 2 (6.7) Treatment: TSF re-application: 1, PO: 1	–
Molepo et al.[40]	1/9 (11.1) Treatment: aggressive debridement, irrigation and TSF re-application	2 (22.2) Treatment: Replacement	–	–	–	–

AT, Achilles tendon; LLD, leg length discrepancy

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Appendix 1

Appendix 1: Full search strategy – Date: 15 December 2021

1	exp fracture fixation/	158,523	13	hexapod.mp.	1,065	25	24 or 8	34,000
2	fractures, bone/	97,307	14	"circular external fixator*". mp.	534	26	fracture non-union/ or fracture healing/	55,370
3	1 or 2	236,711	15	Taylor spatial frame.mp.	549	27	10 or 26	196,372
4	tibia/	78,839	16	TL-HEX.mp.	18	28	25 and 27 and 17	201
5	3 and 4	6,330	17	or/13-16	2,013	29	9 and 12 and 17	163
6	tibia$.ti.	58,986	18	tibia fracture/or tibia shaft fracture/	15,412	30	28 or 29	216
7	fracture$.tw.	60,8181	19	exp fracture treatment/or fracture healing/	15,1789		OVID MEDLINE	72
8	6 and 7	20,972	20	fracture/	89,827		OVID Embase	142
9	5 or 8	25,232	21	19 or 20	22,8747		Cochrane	2
10	[non union or non-union or nonunion or un-united or ununited or delayed union or union or (fractur* adj2 healing)].tw.	169,400	22	tibia/or tibia shaft/	79586	31	remove duplicates from 30	153
11	fractures, ununited/or fracture healing/	56,509	23	21 and 22	6,133			
12	10 or 11	196,122	24	18 or 23	20,796			