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GENERAL ORTHOPAEDICS

Correction of rotational deformities in long bones using guided growth: a scoping review

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- *Purpose:* The objective of this scoping review was to describe the extent and type of evidence of using guided growth to correct rotational deformities of long bones in children.
- *Methods:* This scoping review was conducted in accordance with the JBI methodology for scoping reviews. All published and unpublished studies investigating surgical methods using guided growth to perform gradual rotation of long bones were included.
- *Results:* Fourteen studies were included: one review, three clinical studies, and ten preclinical studies. In the three clinical studies, three different surgical methods were used on 21 children. Some degree of rotation was achieved in all but two children. Adverse effects reported included limb length discrepancy (LLD), knee stiffness and rebound of rotation after removal of tethers. Of the ten preclinical studies, two were *ex vivo* and eight were *in vivo*. Rotation was achieved in all preclinical studies. Adverse effects reported included implant extrusions, LLD, articular deformities, joint stiffness and rebound of rotation after removal of tethers. Two of the studies reported on histological changes.
- *Conclusions:* All studies conclude that guided growth is a potential treatment for rotational deformities of long bones. There is great variation in animal models and surgical methods used and in reported adverse effects. More research is needed to shed light on the best surgical guided growth method, its effectiveness as well as the involved risks and complications. Based on current evidence the procedure is still to be considered experimental.
- *Level of evidence*: 4

Keywords: guided growth; rotational deformity; malrotation; maltorsion; hemiepiphysiodesis

Introduction

Temporary hemiepiphysiodesis, also known as guided growth, was first presented by Haas et al in the late 1940s. It is the principle of changing the direction of bone growth by inhibiting or stimulating growth in selected areas of the physis (growth plate). Since then, it has evolved into a well-established treatment concept for correcting angular deformities of the lower limb in children (1). The concept is that by inhibiting a part of the growth plate, that part will grow less than the other, normal-growing sides, thus changing the direction of growth.

Severe coronal malalignment (bowlegs or knock knees) are treated by spanning one side of the physis (growth plate) with a plate, thereby inhibiting growth on that

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side. Similarly, percutaneous epiphysiodesis using transphyseal screws (PETS) also creates a tether by eccentric placement of the screw (2).

There is emerging evidence that guided growth (3, 4, 5) could also be used to treat rotational deformities in children. Rotational deformities can arise from many causes, for example, congenital, idiopathic, posttraumatic, and iatrogenic. Rotational deformities can cause in-toing, out-toing, as well as pain and thus affect the gait.

In contrast to coronal malalignment, which in skeletally immature individuals most often is corrected by guided growth, malrotation of the lower limb is most commonly treated with surgical osteotomy, de-rotation, and fixation of the realigned bone segments with a plate, intramedullary nail or external fixator (6, 7, 8). This is a more comprehensive treatment compared to guided growth.

By using guided growth, the correction is achieved gradually over a longer period as the patient grows. Avoiding an osteotomy, the surgical procedures are minimally invasive and can be performed as outpatient surgery. It results in less pain for the patient and since there is no weakening of the bone, they can be allowed fully weight-bearing immediately post surgery. This is a major improvement in terms of patients' quality of life because they can return to normal everyday activities such as school and sports almost immediately.

When using guided growth to correct angular deformities, devices (plates, staples, screws, etc.) are placed perpendicular to the physis. In 2013, Arami *et al.* showed that by placing plates in an oblique orientation over the physis, it is possible to induce rotational guided growth in rabbits (4). Since then, similar studies (9, 10, 11, 12) have shown similar promising results, but there are still many questions left unanswered.

These proposed experimental methods have been tested in small animal models and the results are thus not directly transferable to humans. Furthermore, they are limited by the potential drawbacks of not utilizing a specific implant designed for the task and the potential of inducing deformities, leg length discrepancies, and hold the risk of imprecise correction or rebound after device removal.

As the technique of rotational guided growth now has been reported in clinical case series (5, 13, 14) and may appeal to many clinicians as a safe procedure, the aim of this scoping review was to determine the current body of evidence in the literature and to identify possible knowledge gaps or complications that may warrant caution in implementing this procedure as standard care.

Review questions

Which surgical methods for correction of rotational deformities of extremities, by guided growth, have been described in the scientific literature and which research models have been utilized?

Which concerns have previous studies raised regarding outcome and possible complications including, but not limited to, joint deformities, leg length discrepancies, imprecise correction, rebound after device removal, and histological morphology?

Eligibility criteria

Participants

Any published or unpublished study where correction of rotational deformity of extremities by guided growth, has been tested including, but not limited to *ex vivo* and *in vivo* preclinical studies, clinical studies, and preclinical animal studies.

Concept

All surgical methods using guided growth to correct rotational deformities.

Context

All settings including but not limited to hospitals and research facilities.

Types of sources

This scoping review considers all published and unpublished, clinical, and preclinical studies investigating guided growth for correcting rotational deformities in extremities.

Methods

This scoping review was conducted and reported in accordance with the JBI methodology for scoping reviews (15).

Search strategy

The search strategy aimed to find published and unpublished studies including both full-text papers as well as conference proceedings. An initial limited search of MEDLINE was undertaken to identify articles on the topic. The text words contained in the titles and abstracts of relevant articles, and the index terms used to describe the articles were used to develop a

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full search strategy for PubMed, Embase (Elsevier), Cochrane Library (via Embase), Web of Science, and Google Scholar (see Appendix 1, see the section on supplementary materials given at the end of this article). The search strategy, including all identified keywords and index terms, was adapted for each included database and information source. The reference lists of all included sources of evidence were screened for additional studies.

Studies published in any language and any date were included.

Study/source of evidence selection

The primary search was conducted on June 14, 2022, and yielded 406 unique results.

All identified citations were collated and uploaded into Rayyan.ai. Following a consistency check, titles and abstracts were then screened by three independent reviewers for assessment against the inclusion criteria for the review.

Seven studies were included, 87 were marked as potentially relevant, and there were three conflicts.

Potentially relevant sources were retrieved in full, and their citation details imported into Endnote (Clarivate Analytics, Philadelphia, PA, USA). The full text of selected citations was assessed in detail against the inclusion criteria by three independent reviewers.

After a consistency meeting, and full text screening, the three conflicts were resolved, and the result was seven included studies (3, 4, 5, 9, 10, 11, 16) and 399 excluded.

The search was updated January 20, 2023 and yielded 53 unique results, all of which were excluded after same screening procedure as mentioned above.

On February 1, 2023 a search was conducted on Google Scholar. The first 98 search pages (980 results) were screened. Due to a consistent and unresolvable server error, search pages 99 and 100 failed to load. Furthermore, reference lists of all included studies were screened. Together this resulted in the inclusion of additional seven studies (12, 13, 14, 17, 18, 19, 20) (Fig. 1).

Data were extracted from papers included in the scoping review using a data extraction tool developed by the reviewers (see Appendix 2).

Results

A total of 14 studies (10 preclinical (3, 4, 9, 10, 11, 12, 17, 18, 19, 20), 3 clinical (5, 13, 14), and 1 review (16)) were included that examined guided growth for rotational deformities.

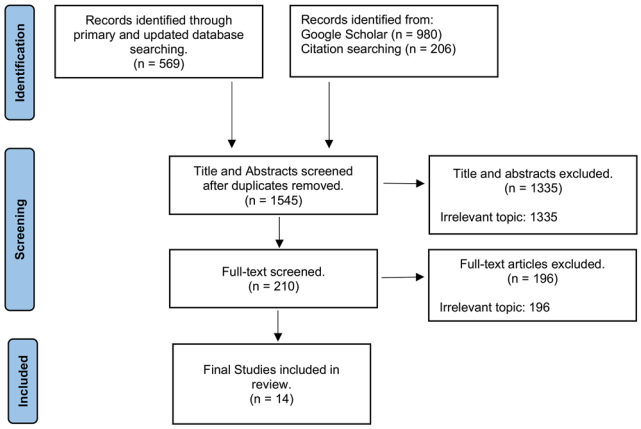

Figure 1

PRISMA flow diagram for the scoping review.

The review (16) covers the use of guided growth for treating angular deformities of lower limbs but includes a paragraph about studies of rotational deformities. All the original material regarding guided growth for rotation was accessible and already included in our scoping review (4, 5, 9, 11).

Two (3, 10) of the ten preclinical studies were *ex vivo*, biomechanical studies.

Two (12, 19) of the eight *in vivo* preclinical studies used an external device, with pins on either side of the growth plate, that relied on manually applied, external torque to achieve rotation of the bones. One (17) was a case report in which the device spanned the stifle joints of a dog and therefore the achieved rotation, presumably, also did occur at the level of the joint. In these three studies, rotation was achieved, but it might not be by physeal guided growth alone.

Two studies (9, 20) used the same rabbits from one animal experiment to report on different measurements.

Two out of the three clinical studies have been published as peer-reviewed papers (5, 14). One clinical study by Balslev-Clausen *et al.* (13) has not been published as a peer-reviewed full-text article, but the study was presented as a poster at the European Paediatric Orthopaedic Society (EPOS) annual meeting in 2022. The abstract of this study have been published in a citable format (13), and the poster is available to us in PDF form.

Study approval

Five (4, 9, 11, 12, 20) of the preclinical, *in vivo* studies reported relevant approval by institutional or ethics committee. For the clinical studies, only Paley *et al.* (14) reported approval by their institutional review board. Metaizeau *et al.* (5) and Balslev-Clausen *et al.* (13) did not report on approval before conducting their studies.

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Surgical method

The most tested method is applying a plate placed obliquely over the physis on each side of the bone (Fig. 2A). This has been tested in preclinical studies on rabbits (4, 9, 11, 20) and Balslev-Clausen *et al.* (13) used the method in their clinical trial.

One study (18) tested a bicortical cannulated screw on either side of the physis connected with a cable on calves. The same principle was applied by Metaizeau *et al.* (5) in 11 children (Fig. 2B).

Paley *et al.* (14) used a method with separated hinge plates connected by FiberTape (Fig. 2C). While the premise of this method is similar to using plates, this method had not been tested preclinically before their study.

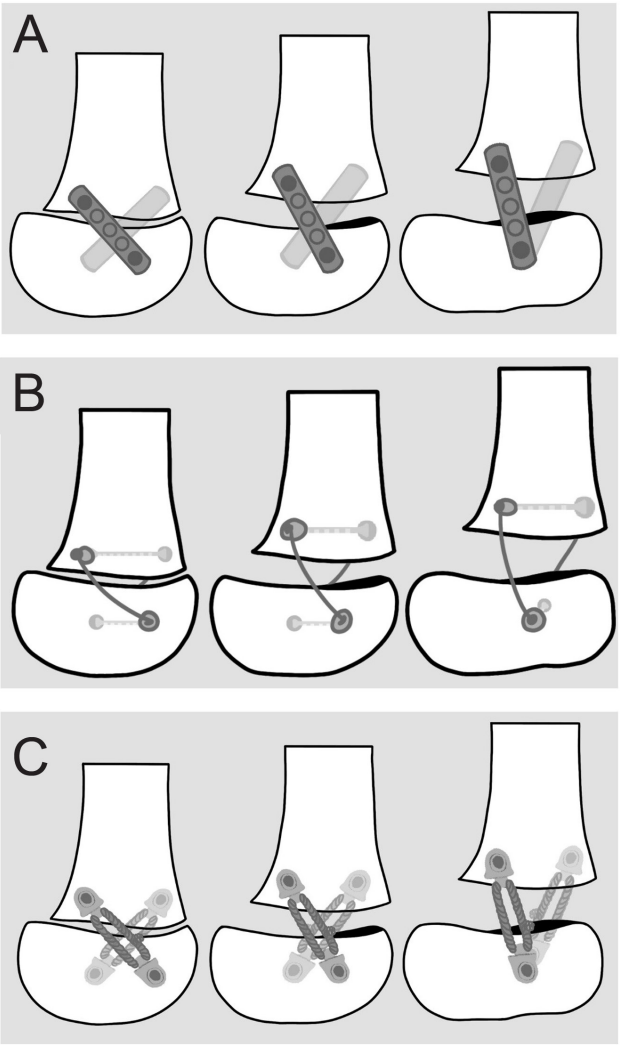

Figure 2

A. Illustration of surgical method for plate placed obliquely over the physis. B. Illustration of surgical method for bicortical cannulated screw on either side of the physis connected with a cable. C. Illustration of surgical method for separated hinge plates connected by FiberTape.

Rotation achieved

All preclinical studies reported significant external rotation achieved with their various surgical methods and animal models. Arami *et al.* (4) achieved internal rotation but this was not statistically significant. All the preclinical studies with internal tethers used a combination of X-ray and CT scans after termination to measure the rotation achieved.

Five studies (4, 12, 18, 19, 20) used the contralateral leg as control and two (9, 11) used both the contralateral and a control group.

Only one study (3), an *ex vivo* study, compared the achieved rotation to a predicted rotation. The mean difference between predicted and achieved rotation was 2.7°–5.0° depending on the measurement method.

Metaizeau *et al.* (5) reported a mean radiological femoral anteversion decrease of 28° after a mean of 21.5 months, suggesting a mean derotation of 1.3° per month. The femoral anteversion was measured radiologically, but it is not specified how, and the precision of the measurement was not indicated.

Balslev-Clausen *et al.* (13) reported successful rotation in three patients (five bone segments) with an average of 9.3° (abstract (13)) or 9.6° (poster). In one patient (one femur, one tibia) there was no rotation, and it was speculated that this was due to lack of growth as surgery was performed too late. In one patient (two femurs) there was no rotation despite growth still occurring in this patient. Direction of rotation was not specified.

Measurements were done using radiostereometric analysis every 3 months for an average of 23.5 months.

Paley *et al.* (14) reported achieved rotation in all eight bone segments (five patients) in their study, with an average of 30° in femur and 9.5° in tibia. Seven out of eight segments were corrected with external rotation and one segment was corrected with internal rotation.

Measurements were done clinically using a goniometer before and after intervention. The precision of this measurement method is not indicated (Tables 1 and 2).

Technical challenges

All preclinical studies focus on external rotation. Arami *et al.* (4) tried to test their method for internal rotation but found that the shape of the medial condyle and the slope of the proximal part of the epiphysis made it difficult to place the medial plate at the correct angle. This underlines that implants must respect the anatomy both on the medial and lateral side of the joint. This issue has not been reported in studies using less rigid devices interconnected by FiberTape or cerclage wire (5, 14, 18).

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Table 1 Overview of clinical studies. All values are mean (range).

	Population			Method		Results		
Study	PTS,† *n*	Age, years	Bone segments	Implant	Control	Rotation achieved	PTS‡, *n*	Measurement
Metaizeau *et al.* (5)	11	10.1 (8.6–12.7)	20 femurs	2 screws + cable	No	1.2°/month	11	Radiological*
Balslev-Clausen *et al.* (13)	5	11.6 (10.4–12.9)	7 femurs, 2 tibiae	PediPlates	No	9.6° (5.8°–13.7°)	3	RSM analysis
Paley and Shannon (14)	5	10.1 (2.6–15.7)	5 femurs, 3 tibiae	Separated hinge plates + FiberTape	No	Femur: 30° (10°–45°); tibia: 9.5° (5°–17°)	5	Clinical

†All were children; *Not specified; ‡Number of patients with successful rotation.
IN, intervention; NR, not reported; PTS, patients; ROM, range of motion, RSM, radiostereometric.

Metaizeau *et al.* (5) reported that they placed the screws too anteriorly in the first 8 knees they operated, before they fully standardized the procedure. This resulted in mild recurvatum in those first 8 knees.

Age at surgery, intervention duration, and follow-up time

The preclinical studies had varying intervention duration and follow-up times.

The average age and range at surgery for the three clinical studies were 10.1 years (8.6–12.7) (5), 11.6 years (10.4–12.9) (13), and 10.1 years (2.6–15.7) (14).

The average duration of intervention reported in the clinical studies were 21.5 (5) and 11.8 (13, 14) months.

Metaizeau *et al.* (5) did not report their follow-up time, and the other two clinical studies (13, 14) had a follow-up time ranging from 2 to 33 months after implant removal.

Rebound effect

Three of the preclinical studies reported on rebound effect after tether removal. Two studies (9, 12) did not find a significant rebound, while Martel *et al.* (18) report a mean rebound of 19.3° 20 months after implant removal. Their mean rotation achieved at implant removal, before rebound, was 24°.

For the clinical studies, Metaizeau *et al.* (5) did not report on rebound effect and Paley *et al.* (14) did not find any rebound after implant removal, measured clinically with goniometer, after an average of 18 months' follow-up (range 2–33 months).

Balslev-Clausen *et al.* (13) reported a rebound of 2.49° in their abstract and 3.65° in their poster, after a an average of 23.5 months' follow-up (range 13.9-30.2 months).

Secondary limb length discrepancy

All the preclinical studies that used internal tethers (4, 9, 11, 18, 20) reported on possible introduction of secondary LLD. All studies in rabbits (4, 9, 11, 20) found significant LLD, while Martel *et al.* (18) did not find significant LLD in their study on calves.

Metaizeau *et al.* (5) found no secondary LLD in patients treated bilaterally, but they reported a theoretical LLD of 12 mm over 2 years measured by comparing the distance between the two screws and comparing it to a theoretical variation.

The other two clinical studies (13, 14) did not report on LLD introduced by the treatment.

Table 2 Follow-up and adverse effects reported in the included studies. Values are reported as mean (range).

	Follow-up, months		**Adverse effects reported**				
Study	IN duration	After implant removal	LLD	Rebound	Articular deformities	Angular deformities (*n*)	ROM (*n*)
Metaizeau *et al.* (5)	21.5	NR	12 mm over 2 years†	–	–	Recurvatum <10° (8)	Transient knee stiffness (10)
Balslev-Clausen *et al.* (13)	11.8 (8.2–17.1)	23.5 (13.9–30.2)*	–	2.49°/3.65°**	–	–	–
Paley and Shannon (14)	11.8 (7–18)	18 (2–33)	–	No	–	No	–

*For patients with successful rotation; **Abstract/poster; †Theoretical.
IN, intervention; LLD, limb length discrepancy; ROM, range of motion.

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Secondary deformities

Two studies reported on articular deformities. Martel *et al.* (18) found no secondary deformities but did not specify what measurements they made. Sevil-Kilimci *et al.* (20), on the other hand, found significant impact on the lateral tibia plateau and medial meniscus, which they report grew significantly in size.

Two preclinical studies and one clinical study reported on secondary angular deformities. Arami *et al.* (4) described a mean difference in lateral distal femoral angle (LDFA) of 13.5° between treated and untreated limbs.

Cobanoglu *et al.* (9) did not find a difference in LDFA between their main group and the sham group, but they did find a mean difference in medial proximal tibial angle (MPTA) of 10° and in femorotibial angle (FTA) of 13°. Comparing the sham group to the rebound group they found no differences in LDFA, MPTA, and FTA, which, according to the authors, indicated a remodeling after plate removal.

Metaizeau *et al.* (5) found a mean recurvatum of less than 10° in the first eight knees they operated. They ascribe this to positioning of the screw and state that after standardizing the surgery technique, this did not occur again.

Paley *et al.* (14) did not report on articular deformities and found no secondary angular deformities, measured clinically, but two patients underwent staged removal of the tethers to treat preexisting angular deformities.

Balselv-Clausen *et al.* (13) did not report on secondary deformities (Tables 3 and 4).

Histology

Moreland's study (19) using an external device on rabbit tibiae reported that during torsion load histological examination showed bending of the cartilaginous columns of the growth plate at the junction of the hypertrophic cells and provisional calcification zones. Primary trabeculae were parallel to these columns. However, histological examination of tibiae that had torsion load removed for 7 days before the rabbit was killed showed that the trabeculae had a normal longitudinal pattern and that there was no histological difference between the operated leg and the control.

Arami *et al.* (4) found a swirling of the growth plate cell columns in the proliferative zone and a normal linear alignment in the hypertrophic zone in the central part of the condyles in the treated femurs. This was not found in the femurs that underwent sham procedure.

Sevil-Kilimci *et al.* (20) found that the growth plates in the operated limbs were higher than those in the control limb in both the main group and the rebound group and did not describe swirling of the columns.

Discussion

Recent advances in epiphysiodesis techniques have opened the possibility of using guided growth to correct rotational deformities in long bones of growing children. This scoping review found a total of 14 studies that have been reported in the years from 1980 to 2022. During our search, 2 pages out of 100 (equivalent to 20 out of 1000 results) on Google Scholar failed to load, despite several attempts on different dates. Google Scholar sorts the results by relevance, and all the included papers were found on the first ten pages. The remaining 88 pages did not contain any papers that met our inclusion criteria. We do not consider this a significant limitation in our search strategy, as we think it is very improbable that the last two pages would have resulted in additional relevant studies.

While initial studies were using external devices, the more recent studies have used internal devices. However, this scoping review also demonstrated that even though the number of studies is increasing in recent years, there are still great variations in surgical techniques used and no universal agreement on indications for treatment or the reporting of outcome measures. We did not find the published clinical studies to be of sufficient quality as to recommend the use of the applied surgical methods.

Before clinical use can be recommended, it must be possible to estimate an expected rotational effect of the applied surgery, which none of the included studies address. Adverse effects like LLD, angular and articular deformities are only examined in the preclinical studies but is not studied in detail in clinical studies.

The *ex vivo*, biomechanical studies (3, 10) are an important, proof-of-concept step in the development of a possible surgical technique, but they do not provide information on the clinical effectiveness of this concept.

Surgical methods used in the included studies vary but can generally be divided into rigid or flexible tethers spanning the growth plate. While rigid tethers are the most tested method in preclinical studies, we found that two (5, 14) out of three clinical studies used flexible tethers, one of which (14) had not been tested preclinically. We found no comparative studies examining the optimal implant design.

Only one (14) of the clinical studies report an approval from institutional board, whereas the other two clinical studies (5, 13) do not report about approval from institutional or ethics committees.

To achieve rotation by guided growth, the patient must have sufficient residual longitudinal growth potential. On the other hand, rotational deformities in the young child with remaining growth may resolve spontaneously. It was therefore surprising to see that rotational correction with guided growth was applied

Table 3 Study details of preclinical, *in vivo* studies excluding one case report (17). All values are mean (range).

	Population			Method			Results		
Study	Model	Bone	Segments	Implant (*n*)	Control (*n*)	Dropout	Rotation achieved	Segments[‖]	Measurement
Moreland (19)	Rabbit	Tibia	35	External rotational device	Contralateral leg	13	Degrees not reported	22	X-ray
Arami *et al.* (4)	Rabbit	Femur	15	Plates + screws	Contralateral leg	2	External: 29°	9	X-ray; CT after termination
							Internal[‡]: 20.7°	4	
Volpon *et al.* (12)	Lamb	Tibia	20	External rotational device	Contralateral leg	1	16°	19	CT after termination
Cobanoglu *et al.* (9)[†]	Rabbit	Tibia	45	Plates + screws (30)	Contralateral leg + sham group (15)	8*	External: 17.1°	7	X-ray biweekly; CT after termination
				Sham: screws only (15)			Sham group: no	15	
							Rebound group: 11°	15	
Lazarus *et al.* (11)	Rabbit	Femur	18	Plates + screws at different angles (13)	Contralateral leg + sham group (5)	0	Significant correlation between rotation and initial plate angle		X-ray biweekly; CT after termination
				Sham: screws only (5)					
Martel *et al.* (18)	Calf	Metacap	8	2 screws + cable	Contralateral leg	0	External: 24°	8	Specially constructed goniometer; X-ray; CT after termination
Sevil-Kilimci *et al.* (20)†	Rabbit	Tibia	30	Plates + screws	Contralateral leg	0	Reported in other study[†]***		Caliper; photos; SolidWorks Software

*Only rotation could not be measured because of excessive sagittal and coronal deformities; [†]Both studies used the same rabbits in two studies; [‡]Not significant; [‖]Number of segments with successful rotation.

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Table 4 Follow-up and adverse effects reported in the preclinical studies. All values are mean (range).

	Follow-up		Adverse effects reported			
Study	Intervention duration (*n*)	After implant removal (*n*)	Limb length discrepancy (*n*)	Rebound (*n*)	Articular deformities	Angular deformities (*n*)
Moreland (19)	1–60 days	None	–	–	–	–
Arami *et al.* (4)	6 weeks	None	6.1 mm (13)	–	–	LDFA: 13.5° (13)
Volpon *et al.* (12)	15 weeks (19)	3 months (9)	–	No	–	–
†Cobanoglu *et al.* (9)	4 weeks (45)	4 weeks (15)	4 mm (15)	No	Reported in other study†	LDFA: no; MPTA: 10°; FTA: 13° (15)
Sham group			No (15)			No (15)
Rebound group			No (15)			No (15)
Lazarus *et al.* (11)	6 weeks	None	≈ 4 mm**(13); 4.7% compared to sham	–	–	–
Martel *et al.* (18)	3 months	20 months	No	19.3° (8)	No	No
†Sevil-Kilimci *et al.* (20)	–		Reported in other study†	Reported in other study†	Lateral tibia plateau and medial meniscus sizes affected	Reported in other study†

**From figure, exact value not reported; †Both these studies used the same rabbits in two studies.
FTA, femorotibial angle; LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle.

in a child as young as 2.6 years of age in one of the clinical studies (14).

It seems imperative that either a very good prediction of remaining growth and achievable rotational correction or a very stringent follow-up is needed to plan for implant removal. The risk of rotational overcorrection has not been addressed in the three clinical studies and they did not address the risk of introducing secondary deformities comprehensively. This is very concerning, as for all the clinically used surgical methods there seems to be a risk of unplanned total or partial growth inhibition as the tethers become parallel to the bone.

It is also crucial that both tethers rotate simultaneously. If one side rotates slower, or stops rotating, it might cause angular deformities. Slower rotation on one side can happen if the implant is placed at a slightly different angle, if there is bone overgrowth or because of implant extrusion. This could explain the angular and articular deformities found by Cobanoglu *et al.* (9) and Sevil-Kilimci *et al.* (20). Moreover, rotational guided growth may alter central knee anatomy, which can be described by the recently established femoral floor angle, femoral width at the physis, femoral notch–intracondylar distance, and the tibial roof angle (2).

This scoping review did not find a universal method of measuring and reporting the achieved rotation. For some preclinical studies, CT scans were obtained but the methods to measure rotations from these CT scans varied. Most studies examined the achieved rotation from x-rays, but also here there were no universal method to measure this. One clinical study (13) performed advanced radiostereometric analysis, although the precision of this method to measure the rotation in this population of children is not reported. Another clinical study (5) examined rotation from radiographs without specifying this method further. The last clinical study (14) examined the rotation by clinical examination alone.

Two preclinical studies (9, 11) compare the achieved rotation to a control group while the rest of the preclinical studies (4, 12, 18, 19, 20) use the contralateral leg for comparison. The clinical studies (5, 13, 14) rely on before/after measurements since most patients are operated bilaterally. As such there is an uncertainty to how much of the achieved rotation can be ascribed to the intervention and how much is due to physiological and spontaneous correction.

Looking at follow-up time after implant removal, the clinical studies (5, 13, 14) all agree that longer follow-up time is needed in future studies. Therefore, the long-term effect of this type of surgery is unknown and future studies should aim for a minimum follow-up of patients until closure of the growth plate to investigate for rebound effect or other adverse effects.

Secondary LLD has been found in several preclinical studies (4, 9, 11), all in rabbits. Martel *et al.* examined for LLD (18) in bovines and they did not find secondary LLD after treatment. Some (14) have argued that this could be due to rabbits being smaller and fast growing, but it is worth noting that the rabbit studies used plates while Martel *et al.* (18) used two screws and a cable, so different surgical methods could also account for this difference. Metaizeau *et al.* (5) used the same method as Martel *et al.* (18) and they reported a theoretical LLD of 12 mm over two years.

Secondary LLD remains an important factor to take into consideration and needs further investigation to clarify the risks involved when using guided growth to correct rotational deformities.

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Further investigation is also needed for other adverse effects like articular and angular deformities as well as rebound effect. Only two (18, 20) of all the included studies report on articular deformities and their findings differ, maybe due to the use of different animals and different surgery methods. Martel *et al.* (18) found no secondary articular deformities using screws and cable in bovine, while Sevil-Kilimci *et al.* (20) found several changes when using plates in rabbits.

Two preclinical studies (4, 9) and one clinical study (5) found secondary angular deformities, but the findings vary, even though both preclinical studies use rabbits and rigid tethers. Possible explanations for this could be the placement of the tethers or an unintentional violation of the growth plate during surgery.

Only three of the preclinical studies (9, 12, 18) report on rebound effect. It is interesting that Martel *et al.* (18) were the only ones to find a significant rebound effect, that had reversed nearly all the achieved rotation 20 months after implant removal.

For the clinical studies rebound was only found by the study using radiostereometric analysis to detect rotation (13).

Histological analysis is very sparse in the included studies with only two preclinical studies using internal tethers reporting on it. Arami *et al.* (4) looked at the growth plate at the central part of the condyles of the treated femur. Sevil-Kilimci *et al.* (20) looked at samples of the growth plate from the tibia but did not specify what part of the growth plate they had sampled.

For rotational guided growth, it can be speculated that the central part of the growth plate would be affected differently than the peripheral parts and the parts adjacent to the tethers. This could explain some of the articular and angular changes that have been reported (4, 9, 18, 20), and it is worth further investigation in future studies.

Going forward, further innovation in this field would benefit greatly from adhering to the IDEAL framework as recommended by the Balliol Collaboration (21). Predefined, consistent outcome measurement, a greater focus on possible adverse effects and longer follow-up time, preferably until closure of the growth plate, is needed to fully understand the effects and risks of this procedure before widespread clinical use can be recommended.

Conclusion

In conclusion, this scoping review describes the published surgical methods for gradual rotation of long bones by guided growth. While all studies report that rotational guided growth works, almost no studies compare the achieved rotation to a preoperative expected rotation. Moreover, uniform reporting of outcome measurements, including adverse effects are lacking. The clinical evidence for correcting rotational deformity by guided growth is sparse. A stepwise introduction with sufficient preclinical investigations and introduction of clinical prospective studies is highly recommended prior to judging whether this new concept can safely replace current surgical treatments.

Supplementary materials
This is linked to the online version of the paper at https://doi.org/10.1530/EOR-23-0149.

Declaration of interest
The authors of this article have recently published a study in cadavers describing a new plate concept for rotational guided growth (1). The plate concept is intended for future commercial use with possible financial benefits for inventor and patentor. It is invented by co-author AAA and patented by the North Denmark Region.

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Author contribution statement
AH (primary investigator): screening of studies, drafting the manuscript. SK: screening of studies, critical revision of manuscript. JDR: screening of studies, critical revision of manuscript. AAA: screening of studies, critical revision of manuscript. OR: screening of studies, critical revision of manuscript. All authors have contributed to this study, revised, and accepted the manuscript as submitted.

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