Guided Growth: Current Perspectives and Future Challenges

Irene Yang, BE/BMedSc

Martin Gottliebsen, MD, PhD

Polina Martinkevich, MD, PhD

Aaron Schindeler, PhD

David G. Little, MBBS, PhD

Investigation performed at Orthopaedic Research and Biotechnology, Kids Research Institute, Westmead, New South Wales, Australia

Abstract

» Guided growth by tethering part of the growth plate is an established technique for the correction of frontal angular deformities about the knee in children.

» A better understanding of the underlying conditions, factors affecting longitudinal growth, and mechanism of response of the growth plate to retardation forces could lead to improvement and expansion of this technique to other sites and indications.

» This review article highlights areas of future research and outlines the possible future of guided growth techniques.

Our current understanding of guided growth stems largely from our experience of using guided growth to treat pediatric knee deformities, such as genu varum and genu valgum. In children, such deformities can be a source of morbidity and disability. If the knee deformity is severe and left uncorrected, it can lead to many complications: genu varum is typically associated with the development and progression of knee osteoarthritis[1]; however, genu valgum has also shown some association with that disease[2-4]. Worsening knee deformities are often associated with an altered gait pattern, which can be prominent and functionally limiting, cause substantial pain and discomfort, and have a negative impact on quality of life[5]. Osteotomies have traditionally been indicated for the correction of these deformities[6] and remain the best solution for multiplanar angular deformities, despite being surgically invasive and prone to complications[6,7].

The principles behind the guided growth technique were revealed by Haas in the 1940s[8,9]. He demonstrated that metal wire loops affixed to a skeletally immature physis cause tethering and attenuation of the growth potential. Blount et al. pioneered the guided growth technique and clearly described the use of stapling, stating that[10,11]: "Angular deformity may be corrected during the growth period. Knock-knee, bowleg, back-knee, flexion deformity, or combinations of these deformities are rapidly overcome." The Blount staple proved to be effective in the treatment of pediatric lower-limb angular deformities by physically limiting the growth on one side of the growth plate. Modern guided growth procedures are relatively noninvasive. They utilize staples[12] or screws and plates[6] to direct longitudinal bone growth. Approaches employing guided growth have gained acceptance as preferred treatments[13,14].

This review summarizes the current achievements of guided growth, highlights areas for further research, and speculates on novel applications of this technique requiring development and validation.

Assessment of Frontal Plane Angular Deformities

Measures of Deformity

Fundamental to treatment is a thorough understanding of the growth pattern of

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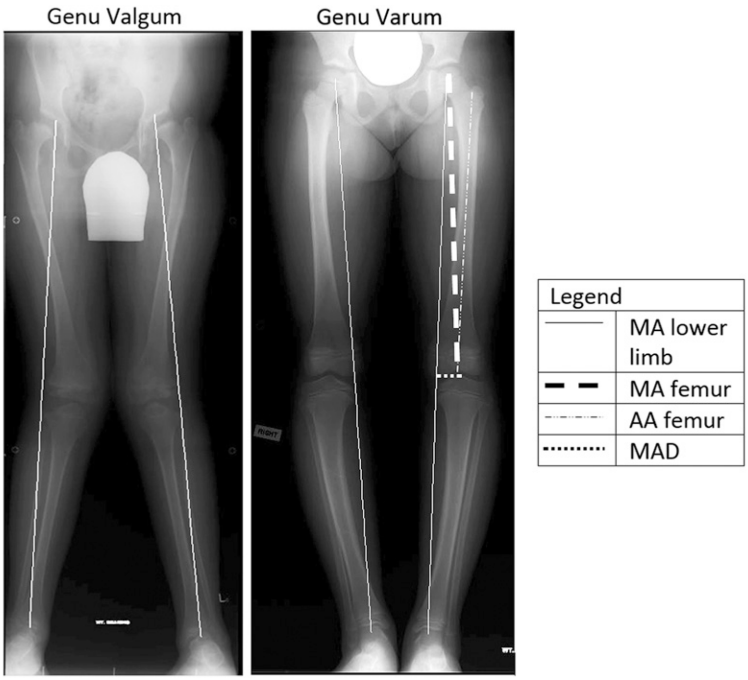

Fig. 1
Radiographs depicting the axes of the bones and the lower limb. MA = mechanical axis, AA = anatomic axis, and MAD = mechanical axis deviation.

the long bones and their axes. The mechanical axis of the lower limb is the line joining the center of the femoral head to the center of the ankle joint. If the mechanical axis is translated medially relative to the center of the knee, genu varum results; conversely, if the axis is translated laterally relative to the center of the knee, genu valgum results. In a frontal plane angular deformity correction, the mechanical axis is most clinically relevant in determining whether the lower-limb alignment requires correction (Fig. 1).

Fig. 2
The mechanical axis deviation classification by zones. (Reproduced, with modification, from: Müller KH, Müller-Färber J. Indications, localization and planning of posttraumatic osteotomies about the knee. In: Hierholzer G, Müller KH, editors. Corrective osteotomies of the lower extremity after trauma. Berlin: Springer; 1985. p 195-223.)

The normal pattern of development of the pediatric tibiofemoral angle is symmetrical and also follows a consistent pattern[15]. Newborns are typically born in varus ("bowlegs"); by 18 to 24 months of age, they reach a neutral angle of 0°. Subsequently, they develop a valgus ("knocked knees") angle around 3 years of age. Typically, a slight valgus is achieved in late childhood and is maintained until maturity.

Three measures are commonly used to assess frontal plane deformities: the mechanical axis deviation, the tibiofemoral angle[16], and the Müller classification[17] by zones. The mechanical axis deviation is measured as the perpendicular distance between the mechanical axis and the center of the knee joint. The angle between the mechanical axis of the tibia and that of the femur is known as the tibiofemoral angle. Close observation and careful evaluation are required for frontal plane tibiofemoral angles that measure outside of 2 standard deviations from the normal mean for a given age group within a defined population[18].

The nomenclature is logical, beginning with the anatomic axis (Fig. 1) or mechanical axis, followed by the medial or lateral orientation and then the reference bone. These include the mechanical lateral distal femoral angle and the anatomic lateral distal femoral angle; these angles describe the distal orientation angle formed between the mechanical axis of the femur and the frontal plane knee joint line on the lateral side of the knee. Complementary to these angles are the mechanical medial distal femoral angle and the anatomic medial distal femoral angle. Similarly, we have the mechanical lateral proximal femoral angle and the anatomic lateral proximal femoral angle, and their complementary angles, the mechanical medial proximal femoral angle and the anatomic medial posterior femoral angle. These same principles are used to describe the tibia. These techniques are the most commonly applied in limb deformity.

TABLE I Etiology of Angular Deformities of the Knee: Genu Varum and Genu Valgum

Etiology Type and Classification	Disorder*
Physiological	Genu varum[90] and genu valgum[89]
Idiopathic	
Genu varum	Blount disease[21]
Trauma	
Genu varum	ACL reconstruction (tibial transphyseal technique)[91] and distal femoral fracture[92]
Genu valgum	ACL reconstruction (tibial transphyseal technique)[93], distal tibial fracture[94], proximal tibial fracture or surgery[95,96], and distal femoral fracture[94]
Infection	
Genu valgum	Osteomyelitis[89] and poliomyelitis[89]
Genu varum	Osteomyelitis[89]
Genetic	
Skeletal dysplasias	
Genu varum	Achondroplasia[97,98], multiple enchondromatosis[99], pseudoachondroplasia[100], osteogenesis imperfecta[89,98], and hereditary multiple exostoses[101]
Genu valgum	Multiple enchondromatosis[99], pseudoachondroplasia[100], hereditary multiple exostoses[101], and Ellis-van Creveld syndrome[102]
Metabolic	
Genu varum	X chromosome-linked hypophosphatemic rickets, vitamin D-resistant rickets, and vitamin D-deficient rickets[98]
Genu valgum	X chromosome-linked hypophosphatemic rickets[89] and renal osteodystrophy[89]
Mucopolysaccharidosis	
Genu valgum	Mucopolysaccharidosis (MPS) IV-A[51] and MPS I and MPS II[52,103]
Neuromuscular	
Genu valgum	Cerebral palsy[89]
Other	
Genu valgum	Juvenile idiopathic arthritis[104] and obesity[105]

*ACL = anterior cruciate ligament.

When analyzing angular knee deformities, the mechanical axis deviation can be measured and can be classified into zones (Fig. 2) according to the classification originally developed by Müller and Müller-Färber[17]. This broader classification can help to guide indications for intervention in childhood. An angular deformity falling within Zone 1 is considered minor and probably within the normal range. Zone 2 is relatively worse and requires follow-up and may require treatment; if untreated, some will progress to Zone 3. Zone 3 is an absolute indication for intervention.

It is recommended that the standardized malalignment test of the mechanical axis of the lower limb be used to determine the abnormality: genu varum or genu valgum. After that, the tibia and femur are individually assessed for deformity. Despite the site of the deformity not always occurring in the growth plate, most surgeons will use guided growth in younger children because of the low morbidity of the procedure.

Indications for Treatment Using Tension Band Plates

Varus and valgus knees are common frontal plane angular deformities, but their exact prevalence is unknown. The unknown prevalence is likely because the deformity can be influenced by a large number of factors including sex[19], ethnicity[20], diet[5], disease status[21], and physical activity[22]. The origin of frontal plane angular deformities can be traced to the distal part of the femur or the proximal part of the tibia[23]. The etiology of pathological frontal plane angular deformities is complex including congenital, acquired, and idiopathic causes. The main etiological factors for the development of varus and valgus malalignment of the knee in pediatric patients are summarized in Table I. This table is not exhaustive but represents a list of common etiologies contributing to genu varum and genu valgum.

In a review of 25 studies, the etiology in patients undergoing guided growth procedures was mostly idiopathic (48%), but bone dysplasias (9%) and Blount disease (12%) were notable[24].

Angular deformity, with or without limb-length inequality, patellofemoral instability, gait disturbance, or cosmetic concerns[25,26] are indications for operative intervention using tension band plates. Some argue that tension band plates with perceived superior performance than staples extend this indication to younger children[27]. Similarly, ankle valgus can be corrected or prevented with guided growth interventions[28].

Early resolution of pathological physis can substantially reduce the likelihood of progressive deterioration associated with prolonged abnormal loading[14]. It is recommended that the operation should occur well before the growth plates have fused to allow for sufficient time to correct the deformity. The exact surgical procedure date should be convenient for the patient[11]. Follow-up until skeletal maturity is crucial to ensure quality of care and to reduce postoperative complications[29].

Guided Growth Surgery for Frontal Plane Knee Deformities

Hemiepiphysiodesis involves unilateral tethering of the growth plate. Additionally, temporary hemiepiphysiodesis is a reversible procedure[30] as it does not permanently damage the growth plate, whereas permanent epiphysiodesis procedures, such as percutaneous drill epiphysiodesis, results in targeted ablation of a selected area of the growth plate[31].

The development of new implant designs parallels the evolution of the surgical procedure (Table II). The Blount staple[11] and the tension band plates (e.g., Eight-Plate; Orthofix)[6] are the most common implants used for guided growth. Although there was early success using the Blount staple, the

TABLE II Surgical Techniques (Listed in Chronological Order) Used for Guided Growth

Surgical Techniques	Effective Surgical Tool	Implant*	In Current Clinical Use
Permanent hemiepiphysiodesis			
Open hemiepiphysiodesis	Bone graft	NA	Rarely
Percutaneous hemiepiphysiodesis (closed technique)	Drill	NA	Rarely
Temporary hemiepiphysiodesis			
Tension loop	Wire loop	NA	No
Percutaneous hemiepiphysiodesis (closed technique)	Transphyseal screws	Cannulated screws	Yes[63-65]
Partial epiphysiodesis/hemiepiphysiodesis	Using staples	Staple Fixation System	Yes[40]
	Using tension band plate with bone screws	Eight-Plate	Yes[40]
		PediPlate	Yes[43]
		Peanut Growth Control Plating System	Yes[36]
		The Hinge Plate Pediatric Plating System	Yes[36]

*NA = not applicable.

popularity of Blount staples has declined over time despite the Blount staple and the tension band constructs both exhibiting effective correction of frontal plane angular deformities with similar effects on the growth plate[32]. Nevertheless, the Blount staple remains a competitive implant for the treatment of limb-length discrepancy[33].

Currently, the most common surgical technique is hemiepiphysiodesis using tension band plates, first described by Stevens[34]. In this technique, the physis is identified by fluoroscopy. After the physis is located, a 2.5 to 4-cm incision is made without damaging the periosteum. A Keith needle is inserted into the physis at, or just posterior to, the mid-sagittal plane and the Eight-Plate is centered over this wire. Two 1.6-mm guidewires are inserted and the cortex is drilled 5 mm deep. Lastly, two 4.5-mm self-tapping screws are used to secure the implant.

Recent studies have shown that other modified techniques may yield improved secondary outcomes compared with Stevens' original technique. Masquijo et al.[35] directly compared the Stevens technique with a modified Paley technique for Eight-Plate insertion. The modified Paley technique[35] differs in that a 1.6-mm guidewire is inserted into the epiphysis, appropriately placed for the plate size. The second guidewire is inserted in the metaphysis at a divergent angle. In this study, the modified Paley technique was found to reduce operative time by 35%, radiation exposure by 67%, and incision size by 15%. That study showed that modifications to standard techniques can affect the radiation exposure and operative times.

Clinical Outcomes of Hemiepiphysiodesis

The outcomes of temporary hemiepiphysiodesis using Blount staples and tension band plates are reported in the literature, demonstrating overall high success rates with minimal complications[6,28,36,37]. The

TABLE III Evidence Regarding Staple and Tension Band Plates Used for Temporary Hemiepiphysiodesis*

Reference	Implant Used	No. of Patients	Mean Age *(yr)*	No. of Deformities	Successful Correction *(% cases)*	Rate of Correction *(deg/yr)*	Complications
Zuege[10]	Blount staple	56	11	82	87	NA	Overcorrection and undercorrection
Stevens[6]	Eight-Plate	34	10	65	97	NA	Loosening of screws, infection
Burghardt[30]	Eight-Plate	43	9	54	93	7.8	Failure due to lack of growth potential, previous permanent physeal damage, underlying illness
Wiemann[106]	Blount staple and Eight-Plate	48	12.6 (Blount staple), 11.1 (Eight-Plate)	63 (24 Eight-Plate, 39 Blount staple)	NA	10	Staple extrusion, screw backing out, screw breakage
Jelinek[46]	Blount staple and Eight-Plate	35	13 (Blount staple), 11 (Eight-Plate)	61	NA	3.6 (Eight-Plate), 4.8 (Blount staple)	Overcorrection, implant migration
Shin[36]	Peanut Plate, Eight-Plate and Hinge Plate	52	11.7	NA	NA	6.6 (Eight-Plate), 4.68 (Hinge Plate), 6.12 (Peanut Plate)	Broken cannulated screws (Peanut Plate), screw pullout (Peanut Plate and Eight-Plate)
Hosseinzadeh[43]	Blount staple, Eight-Plate, and PediPlate	77	11.6	188	NA	4.16 (Blount staple), 2.09 (Eight-Plate), 4.34 (PediPlate)	Broken screw, knee stiffness, screw backing out, reduction complications, screw breakage

*NA = not available.

complication rate is low, but numerous adverse events have been reported (Table III), although there are few empirical data on their relative frequency. Overall, the complication rate, particularly involving implant loosening, is <10%.

Complications of Hemiepiphysiodesis

Table IV offers insight into common complications reported with Blount staples and the various tension band plates in the literature.

With regard to failure to correct, one review identified that risk factors include body mass index (BMI), age, and underlying etiology[24]. Of the identified failures, 14 of 32 were of Blount disease cases. For patients with a high BMI, solid screws are recommended to reduce screw fracture and subsequent failure to correct[38]. Osteopenic conditions may also lead to failure to correct as the screws or the staples migrate, and the use of tension band plates does not impart enough of a tether to change growth direction in patients with osteopenia[39].

The heterogeneous nature of reporting of outcome measures presents challenges in directly comparing the Blount staples to tension band plates for temporary hemiepiphysiodesis. Despite this, little difference between the primary outcomes for these implants has been found[40-42]. Additionally, no significant difference in deformity rate correction were found using various tension band plates (Peanut Plate [Zimmer Biomet], Eight-Plate, and Hinge Plate [Pega Medical]), and all were deemed safe for temporary hemiepiphysiodesis[36]. In one comparative study, the Blount staple and PediPlate (OrthoPediatrics) were seen to correct angular deformity faster than the Eight-Plate; however, these findings are controversial because of inconsistent and variable study design parameters[43].

Despite similar primary outcome results for both Blount staples and tension band plates, surgeons prefer tension band plates for their perceived superior secondary outcome measures such as lower complication rates[40,44], minimally invasive operative technique, more accurate placement[45], and faster implantation and removal time[46].

Rebound and Recurrence

Many of Blount's comments from 1949, based on his initial observations of epiphysiodesis using Blount staples, are still relevant today. One example is the rebound phenomenon, in which malalignment of the mechanical axis of the lower limb partially recurs after surgical correction. The rebounding phenomenon remains an ongoing issue with temporary hemiepiphysiodesis. Factors such as patient age, BMI, the rate of angular deformity correction, and initial pathology have been found to be associated with the rebound phenomenon[47].

Preclinical studies have shown rebound to be unpredictable, and when present, it was not always immediate following implant removal[48]. Once implanted, individual variation in growth patterns makes growth prediction difficult. Timing and duration of treatment are usually based on clinical observation, and it has been suggested that skeletal maturity is more relevant than calendar age[46].

In 1971, Blount found that 50% of growth is retarded at the stapled epiphysis

TABLE IV Complications Associated with Staple and Tension Band Plates

Complications	Staples	Tension Band Plates
Pain	Hosseinzadeh[43]	Gyr[107]
Effusion		Klatt[37]
Infection	Degreef[12], Stevens[56]	Klatt[37], Al-Aubaidi[61], Ballal[108]
Fracture		Al-Aubaidi[61]
Stiffness		Hosseinzadeh[43], Jelinek[46]
Implant loosening	Spiro[60]	Burghardt[30]
Migration	Zuege[10], Kanellopoulos[109]	Jelinek[46], Oda[66], Ballal[108], Heflin[110]
Extrusion	Zuege[10], Hosseinzadeh[43], Wiemann[106], Kanellopoulos[109]	Shin[36], Kumar[40], Hosseinzadeh[43], Wiemann[106]
Implant breakage	Hosseinzadeh[43], Mielke[111]	Shin[36], Hosseinzadeh[43], Burghardt[77], Wiemann[106], Gyr[107], Heflin[110]
Difficulty removing implant	Blount[49]	
Implant failure to correct deformity	Klatt[37], Kumar[40], Hosseinzadeh[43]	Burghardt[30], Kumar[40], Hosseinzadeh[43], Boero[44], Wiemann[106]
Overcorrection	Zuege[10], Degreef[12]	Jelinek[46]
Rebounding	Zuege[10], Degreef[12]	Burghardt[30], Klatt[37], Boero[44]
Premature growth plate closure		Ballal[108]
Residual deformity requiring surgical intervention	Degreef[12], Wiemann[106], Mielke[111]	
Limb-length discrepancy >1 cm	Kumar[40]	Kumar[40]

within the first 6 months of epiphyseal stapling[49]. Then 80% to 90% growth retardation is seen in the stapled epiphysis for the remaining period that staples are implanted. Normal growth resumes after implant removal, with temporary growth acceleration. This resumption of growth is possibly why rebounding occurs. In a study of pigs implanted with Eight-Plates and Blount staples, areas of abundant disorganized cartilage tissue were found and enlargement of the growth plate occurred[32].

Distinguishing rebound, a temporary phenomenon, from recurrence is important. Recurrence is the continual development of pathological malalignment of the mechanical axis of the lower limb. Rebound occurs as the untethered growth plate responds with temporary overgrowth. Recurrence occurs in children with underlying disorders[50] such as mucopolysaccharidoses[51,52], uncontrolled forms of rickets (Fig. 3), and some bone dysplasias[53].

Future Possibilities Utilizing Guided Growth

Indications for guided growth in children have broadened to include the treatment

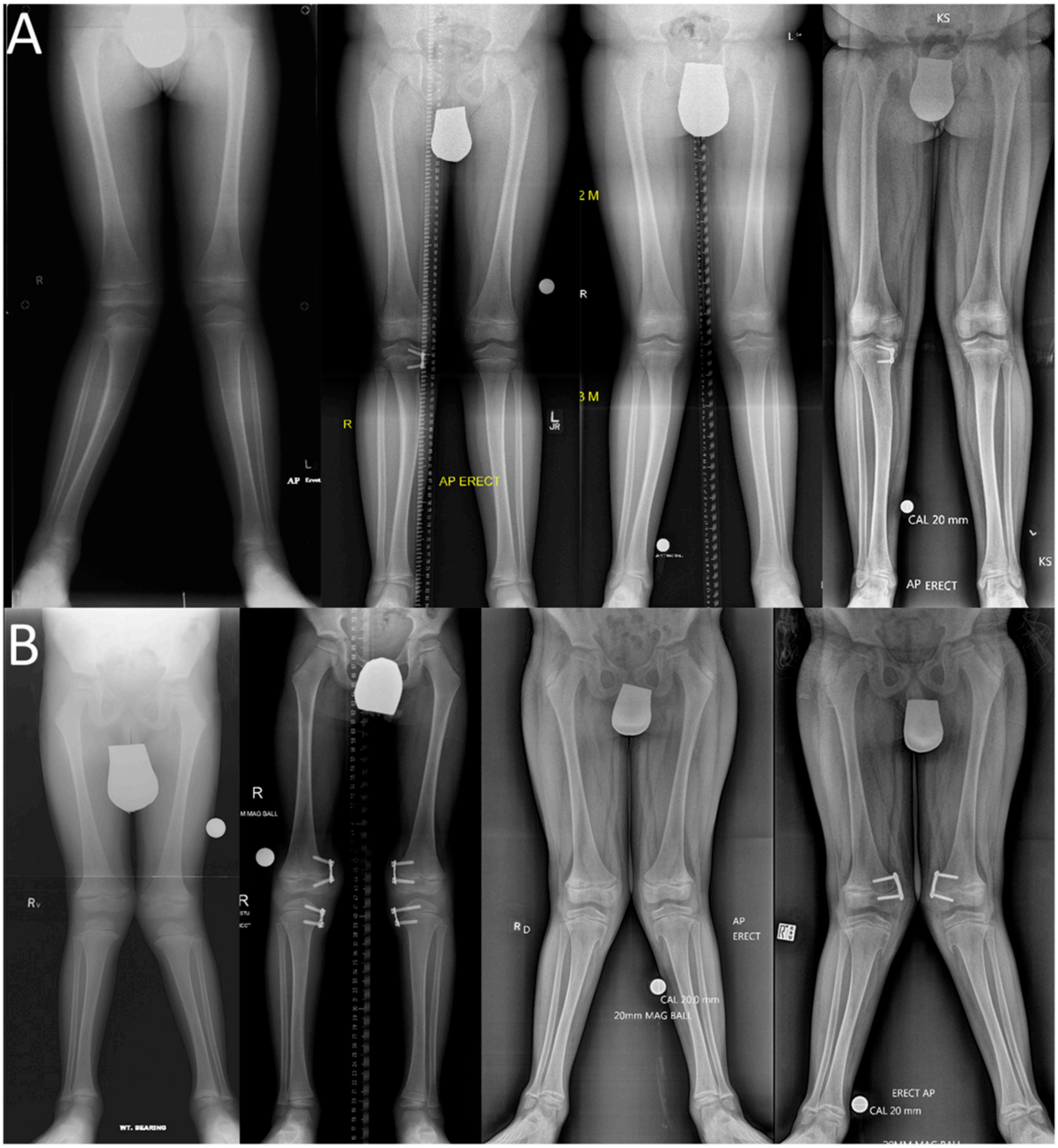

Fig. 3

Figs. 3-A and 3-B Radiographs. **Fig. 3-A** A child with a knee valgus deformity after a Cozen fracture. Younger patients are at risk of the rebound phenomenon, in which removal of the tether results in overgrowth, sometimes requiring retreatment. **Fig. 3-B** A patient with cystinosis leading to ricketic changes. Patients with these types of underlying disorders are at risk of recurrence.

of limb-length discrepancies[54], oblique plane deformity[6], sagittal plane deformities such as genu procurvatum and genu recurvatum[39], and early-onset scoliosis[55]. Although guided growth is already used to correct ankle valgus[56], the use of guided growth for the treatment of other ankle deformities could also be considered. Indeed, the possibility of utilizing a simple technique to improve or eliminate a deformity is the impetus for the growing interest and research in guided growth.

Guided Growth Application: Expanding the Use of This Treatment

To date, the application of the guided growth technique using tension band plates has been predominantly limited to the major long bones. Its success in these regions has sparked an interest to explore the utilization of this technique to treat similar deformities in other regions of the body. Application of this technique in novel regions is challenging: the region may be poorly accessible or may be occluded by surrounding anatomy (for insertion and harvesting of the guided growth implant), or there may be less bone available for staple or screw insertion.

Guided Growth in the Hip

There are emerging reports of using percutaneous screw techniques to slow medial growth of the proximal femoral physis, creating a gradual varus angulation. In 2012, Stevens and Novais[57] applied guided growth in the hip of 3 patients with Schmid-type metaphyseal dysplasia. Lateral tethering of the trochanteric apophysis increased the femoral neck-shaft angle. Complications of this technique include the physis growing off the screw and having to be reimplanted. Careful screw positioning is required as only a few threads can cross the medial growth plate. In 2015, Agus et al.[58] reported on Type-II osteonecrosis in developmental dysplasia of the hip and on the efficacy of guided growth for correction of valgus tilt in the femoral head. Lee et al.[59] reported on guided growth in cerebral palsy to retard hip displacement; however, to our knowledge, that study has yet to be validated, and the many complexities of neuromuscular disease weaken this potential indication. Clinical studies with long-term outcomes of this approach are necessary to determine the efficacy of guided growth for deformity correction around the hip joint. The potential benefit to limit invasive osteotomies remains a major impetus for this research.

Anterior Knee: Guided Growth for Sagittal Plane Angular Deformities

Patients with cerebral palsy often present with sagittal plane angular deformities (e.g., fixed knee flexion deformity). Guided growth has been shown to correct sagittal plane angular deformities by placing the tension band plates on the anterior surface of the distal part of the femur[37,60]. Although poorly reported in the literature, there is an increasing clinical appreciation of patient discomfort following an anterior hemiepiphysiodesis surgical procedure[61].

Guided Growth in the Ankle

Transphyseal screws and tension band plates have been trialed for guided growth of progressive ankle valgus[56,62]. Concern has been raised regarding the use of rigid transphyseal screws, as they can lead to infection[63,64]. Tension band plates have been associated with fewer implant complications than transphyseal screws[65]. The successful use of tension band plates in the distal part of the tibia for the correction of ankle valgus has been demonstrated[28]. In general, guided growth for the treatment of ankle valgus is perceived as safe and well tolerated by some authors[56]; however, others have prompted caution of the use of tension band plates in cases of small epiphyses and osteopenic bones[66].

Sporadic reports have examined correction of equinus deformity at the ankle. In one study on clubfeet, some radiographic measures showed improvement, but no clinically relevant dorsiflexion in the ankle was clearly demonstrated[61].

Guided Growth in the Foot

Fox and Smith[67] reported a case study on hemiepiphysiodesis by excising a portion of the growth plate on the lateral aspect of the base of the first metatarsal and replacing it with a calcaneal bone graft to treat hallux valgus. In this case report, hemiepiphysiodesis was effective and safe and had no major complications. This procedure involved partial excision of the growth plate, which is irreversible. In later years, staples similar to the Blount staple were used for hemiepiphysiodesis[68]. Future work might explore the development of an implant similar to a tension band plate specific for the region, which can offer similar advantages such as adaptability and reversibility.

Similar to guided growth in the lower limb, guided growth in the foot can be used for angular deformities in various planes. Future work can explore the design of an implant for the treatment of sagittal plane angular deformities in the foot, such as pes cavus.

Guided Growth for Rotational Deformities

Guided growth could offer clinical advantages in the treatment of rotational angular deformities and this has been successfully demonstrated in animal studies[69-71]. Arami et al.[69] showed that oblique placement of 2 plates, placed on the medial and the lateral side of the physis of a rabbit femur, can significantly affect the rotational profile ($p = 0.008$). Similarly, a study in rabbits ($n = 45$) assessed the effectiveness of using plates for the treatment of rotational angular deformities and the rebound effect[71]. It was found that treatment using obliquely placed plates achieved significant mean rotational torsion angle changes ($p < 0.001$). Furthermore, using screws alone did not produce a significant change in mean rotational torsion angle in the rabbits treated ($p = 0.2$). Animal research has demonstrated one major disadvantage in using oblique tension band plates for rotational guided growth: at the end of rotation, the tension band plates are longitudinally aligned and therefore inhibit longitudinal growth. Future research can aim to design a solution that addresses this caveat.

Despite successful results in animals, to our knowledge, there have been no results from human clinical studies. Rotational angular deformities, such as femoral anteversion, are still frequently corrected by osteotomy[16]. Furthermore, the current lack of understanding of timing may limit the applicability of this technique in clinical practice.

Guided Growth in the Spine: Scoliosis and Spinal Deformities

A noninvasive magnetically controlled growing rod has also been designed for the management of progressive early-onset scoliosis[72]. These rods connect 2 spinal levels with subcutaneous rods, which are intended to control scoliosis progression while allowing growth. To direct spinal growth using guided growth implants, each vertebral body would require growth manipulation, which is more complex.

Since the early success of the staple used for guided long bone growth, surgeons have attempted to apply a similar tethering technique in the spine to treat growing patients with progressive early-onset scoliosis[55,73,74]. Although some early results have been promising, other cases fail and still require correction and fusion, highlighting the need for further research to refine possible indications for this technique.

There is controversy surrounding the application of guided growth in the spine as the concept is relatively new[75] and complication rates remain high[76]. Complications are mainly due to implant-related failure, and improvements to implant design and more surgical experience could yield safer and more superior results[72].

Implant-Related Design

There is a need to design implants with greater reliability. Tension band plates have established implant issues: inadequate purchase of the screws can cause screw extrusion, and screw breakages are common[24,36,43,77]. Soft-tissue irritation resulting in pain and discomfort at the implantation site has been reported[78]. Pain occurs as a result of normal day-to-day movements causing friction between local soft tissue and the prominent screw head, which protrudes above the surface of the bone. Although this pain is evident in guided growth for frontal plane angular deformities, it has been more apparent in the correction of sagittal plane angular deformities. Macwilliams et al.[79] reported on the possibility of pain and crepitus in patients with cerebral palsy who had plates implanted in the anterior aspect of the knee. Screw-head prominence worsens with gradual screw divergence following longitudinal growth of the bone, perpetuating the issue. Ongoing research aims to improve the implant design and reduce this issue. In the future, the application

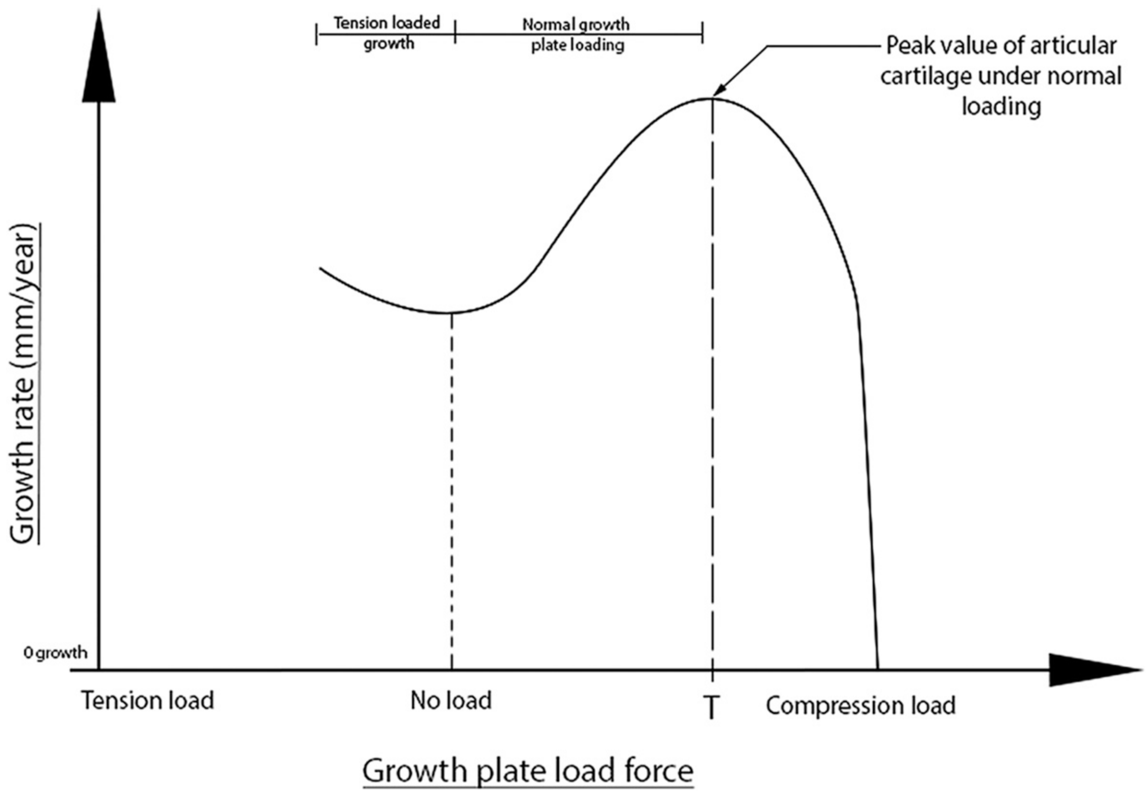

Fig. 4

A graph showing the growth plate response to mechanical loads. T is the threshold load value that inhibits longitudinal growth. (Reproduced, with modification, from: Frost HM. Intermediary organization of the skeleton. Boca Raton, FL: CRC Press; 1986. Reproduced with permission.)

of guided growth in the ankle and foot regions will be of greater concern, if prominence issues are not addressed.

The Growth Plate Response

The exact mechanism of the growth plate response to mechanical loading is unclear[14,80,81]. Bone growth is affected by systemic, local, and mechanical factors[82]. Mechanically, mild tension and compression encourage longitudinal bone growth, whereas compression loads above an ill-defined threshold inhibit longitudinal bone growth. This threshold value is crucial to determining whether spontaneous resolution will occur to restore the mechanical axis, or whether surgical intervention is necessary. In contrast, a growth plate under large enough compressive forces can cease longitudinal growth (Fig. 4)[83]. In a coupled in vitro (chondrogenic cell line) and in vivo (chicken) study, it was shown that chondrocytes' primary cilia in a growth plate have mechanosensing capabilities enabling the detection of mechanical loads[80].

Hemiepiphysiodesis timing is important when considering guided growth treatment[28]. Some growth prediction methods exist[84-86] that provide useful approximations[11]. The typical growth rate for the distal part of the femur is 0.95 cm/year, and for the proximal part of the tibia it is 0.64 cm/year[87]. Nevertheless, the exact timing for each patient currently requires case-by-case analysis[11], posing a challenge for less experienced surgeons. Preoperatively, this influences the timing of surgical treatment. Postoperatively, complications arising from the uncertainty of the growth plate response can yield unpredictable results[88], with undercorrection or overcorrection remaining a common problem[12,89]. Better methods are required to minimize undercorrection and overcorrection and rebound or recurrence in guided growth treatment.

Although this issue persists, a proposed interim solution involves the removal of the metaphyseal screw, leaving the plate and the epiphyseal screw remaining in situ. In the event of rebounding, a less invasive revision surgical procedure replacing only the metaphyseal screw is required. The long-term outcome of this mitigating approach is not available.

Conclusions

Over time, the guided growth technique has increasingly supplanted more invasive and high-impact osteotomies. Extensive experience with guided growth over time has improved treatment outcomes and has unveiled areas for potential improvement. These target both surgical procedures and implant design.

Guided growth is used chiefly to correct angular knee deformities, but many opportunities exist to improve the utilization of this technique in the anterior aspect of the knee and the spine and to expand indications in sites such as the ankle and the foot. Guided growth also has the potential to treat a large number of pediatric rotational deformities, if the many challenges of suitable implant design can be overcome. A specialized implant for the foot and ankle may widen indications and may improve patient comfort.

In conclusion, guided growth is a well-established technique that also holds a promising potential future in a wider patient population than is currently considered, but this will require ongoing research and development of both techniques and implants.

Irene Yang, BE/BMedSc[1],
Martin Gottliebsen, MD, PhD[2],
Polina Martinkevich, MD, PhD[2],
Aaron Schindeler, PhD[1,3],
David G. Little, MBBS, PhD[1,3]

[1]Orthopaedic Research and Biotechnology, Kids Research Institute, Westmead, New South Wales, Australia

[2]Department of Children's Orthopaedics, Aarhus University Hospital, Aarhus, Denmark

[3]Discipline of Child and Adolescent Health, The University of Sydney, Sydney Medical School, The Children's Hospital at Westmead Clinical School, Sydney, New South Wales, Australia

E-mail address for I. Yang: irene.yang@sydney.edu.au
E-mail address for M. Gottliebsen: martin.gottliebsen@gmail.com
E-mail address for P. Martinkevich: polina.martinkevich@gmail.com
E-mail address for A. Schindeler: aaron.schindeler@sydney.edu.au
E-mail address for D.G. Little: david.little@health.nsw.gov.au

References

1. Brouwer GM, van Tol AW, Bergink AP, Belo JN, Bernsen RM, Reijman M, Pols HA, Bierma-Zeinstra SM. Association between valgus and varus alignment and the development and progression of radiographic osteoarthritis of the knee. Arthritis Rheum. 2007 Apr;56(4):1204-11.

2. Bastick AN, Belo JN, Runhaar J, Bierma-Zeinstra SM. What are the prognostic factors for radiographic progression of knee osteoarthritis? A meta-analysis. Clin Orthop Relat Res. 2015 Sep;473(9):2969-89. Epub 2015 May 21.

3. Felson DT, Niu J, Gross KD, Englund M, Sharma L, Cooke TD, Guermazi A, Roemer FW, Segal N, Goggins JM, Lewis CE, Eaton C, Nevitt MC. Valgus malalignment is a risk factor for lateral knee osteoarthritis incidence and progression: findings from the Multicenter Osteoarthritis Study and the Osteoarthritis Initiative. Arthritis Rheum. 2013 Feb;65(2):355-62.

4. Sharma L, Chmiel JS, Almagor O, Felson D, Guermazi A, Roemer F, Lewis CE, Segal N, Torner J, Cooke TD, Hietpas J, Lynch J, Nevitt M. The role of varus and valgus alignment in the initial development of knee cartilage damage by MRI: the MOST study. Ann Rheum Dis. 2013 Feb;72(2):235-40. Epub 2012 May 1.

5. Nia FR, Daneshmandi H, Irandoust KH. Prevalence of genu valgum in obese and underweight girls. World J Sport Sci. 2008;1(1):27-31.

6. Stevens PM. Guided growth for angular correction: a preliminary series using a tension band plate. J Pediatr Orthop. 2007 Apr-May;27(3):253-9.

7. Mycoskie PJ. Complications of osteotomies about the knee in children. Orthopedics. 1981 Sep 1;4(9):1005-15.

8. Haas SL. Retardation of bone growth by a wire loop. J Bone Joint Surg. 1945;27(1):25-36.

9. Haas SL. Mechanical retardation of bone growth. J Bone Joint Surg. 1948;30(2):506-12.

10. Zuege RC, Kempken TG, Blount WP. Epiphyseal stapling for angular deformity at the knee. J Bone Joint Surg Am. 1979 Apr;61(3):320-9.

11. Blount WP, Clarke GR. Control of bone growth by epiphyseal stapling; a preliminary report. J Bone Joint Surg Am. 1949 Jul;31(3):464-78.

12. Degreef I, Moens P, Fabry G. Temporary epiphysiodesis with Blount stapling for treatment of idiopathic genua valga in children. Acta Orthop Belg. 2003 Oct;69(5):426-32.

13. Sabharwal S, Louie KW, Reid JS. What's new in limb-lengthening and deformity correction. J Bone Joint Surg Am. 2014 Aug 20;96(16):1399-406.

14. Eastwood DM, Sanghrajka AP. Guided growth: recent advances in a deep-rooted concept. J Bone Joint Surg Br. 2011 Jan;93(1):12-8.

15. Das SP, Pradhan S, Sahoo PK, Mohanty RN, Das SK. Our experience with correction of angular deformities of knee by flexible figure of 8-Plate hemiepiphysiodesis. IJPMR 2012 Jun;23(2):68-73.

16. Paley D. Radiographic assessment of lower limb deformities. In: Principles of deformity correction. Berlin: Springer; 2002. p 31-60.

17. Müller KH, Müller-Färber J. Indications, localization and planning of posttraumatic osteotomies about the knee. In: Hierholzer G, Müller KH, editors. Corrective osteotomies of the lower extremity after trauma. Berlin: Springer; 1985. p 195-223.

18. Mathew SE, Madhuri V. Clinical tibiofemoral angle in South Indian children. Bone Joint Res. 2013 Aug 14;2(8):155-61.

19. Cahuzac JP, Vardon D, Sales de Gauzy J. Development of the clinical tibiofemoral angle in normal adolescents. A study of 427 normal subjects from 10 to 16 years of age. J Bone Joint Surg Br. 1995 Sep;77(5):729-32.

20. Karimi-Mobarake M, Kashefipour A, Yousfnejad Z. The prevalence of genu varum and genu valgum in primary school children in Iran 2003-2004. J Med Sci. 2005;5(1):52-4.

21. Sabharwal S. Blount disease: an update. Orthop Clin North Am. 2015 Jan;46(1):37-47. Epub 2014 Oct 12.

22. Asadi K, Mirbolook A, Heidarzadeh A, Mardani Kivi M, Emami Meybodi MK, Rouhi Rad M. Association of soccer and genu varum in adolescents. Trauma Mon. 2015 May;20(2):e17184. Epub 2015 May 25.

23. Shapiro F. Pediatric orthopedic deformities. San Diego: Elsevier Science; 2002.

24. Shabtai L, Herzenberg JE. Limits of growth modulation using tension band plates in the lower extremities. J Am Acad Orthop Surg. 2016 Oct;24(10):691-701.

25. Guzman H, Yaszay B, Scott VP, Bastrom TP, Mubarak SJ. Early experience with medial femoral tension band plating in idiopathic genu valgum. J Child Orthop. 2011 Feb;5(1):11-7. Epub 2010 Dec 8.

26. Fillingham YA, Kroin E, Frank RM, Erickson B, Hellman M, Kogan M. Post-operative delay in return of function following guided growth tension plating and use of corrective physical therapy. J Child Orthop. 2014 May;8(3):265-71. Epub 2014 May 13.

27. Burghardt RD, Herzenberg JE, Standard SC, Paley D. Temporary hemiepiphyseal arrest using a screw and plate device to treat knee and ankle deformities in children: a preliminary report. J Child Orthop. 2008 Jun;2(3):187-97. Epub 2008 Mar 26.

28. van Oosterbos M, van der Zwan AL, van der Woude HJ, Ham SJ. Correction of ankle valgus by hemiepiphysiodesis using the tension band principle in patients with multiple hereditary exostosis. J Child Orthop. 2016 Jun;10(3):267-73. Epub 2016 May 27.

29. Kemppainen JW, Hood KA, Roocroft JH, Schlechter JA, Edmonds EW. Incomplete follow-up after growth modulation surgery: incidence and associated complications. J Pediatr Orthop. 2016 Jul-Aug;36(5):516-20.

30. Burghardt RD, Herzenberg JE. Temporary hemiepiphysiodesis with the Eight-Plate for angular deformities: mid-term results. J Orthop Sci. 2010 Sep;15(5):699-704. Epub 2010 Oct 16.

31. Métaizeau JP, Wong-Chung J, Bertrand H, Pasquier P. Percutaneous epiphysiodesis using transphyseal screws (PETS). J Pediatr Orthop. 1998 May-Jun;18(3):363-9.

32. Gottliebsen M, Rahbek O, Poulsen HD, Møller-Madsen B. Similar growth plate morphology in stapling and tension band plating hemiepiphysiodesis: a porcine experimental histomorphometric study. J Orthop Res. 2013 Apr;31(4):574-9. Epub 2012 Nov 28.

33. Siedhoff M, Ridderbusch K, Breyer S, Stücker R, Rupprecht M. Temporary epiphyseodesis for limb-length discrepancy. 8- to 15-year follow-up of 34 children. Acta Orthop. 2014 Dec;85(6):626-32. Epub 2014 Sep 5.

34. Stevens PM. Guided growth: 1933 to the present. Strategies Trauma Limb Reconstr. 2006;1(1):29-35.

35. Masquijo JJ, Lanfranchi L, Torres-Gomez A, Allende V. Guided growth with the tension band plate construct: a prospective comparison of 2 methods of implant placement. J Pediatr Orthop. 2015 Apr-May;35(3):e20-5.

36. Shin YW, Trehan SK, Uppstrom TJ, Widmann RF, Green DW. Radiographic results and complications of 3 guided growth implants. J Pediatr Orthop. 2016 Jul 11. [Epub ahead of print].

37. Klatt J, Stevens PM. Guided growth for fixed knee flexion deformity. J Pediatr Orthop. 2008 Sep;28(6):626-31.

38. Kadhim M, Hammouda AI, Herzenberg JE. Solid screw insertion for tension band plates: a surgical technique tip. J Child Orthop. 2016 Aug;10(4):307-11. Epub 2016 Jun 16.

39. Masquijo JJ, Firth GB, Sepúlveda D. Failure of tension band plating: a case series. J Pediatr Orthop B. 2016 Jul 8. Epub 2016 Jul 8.

40. Kumar A, Gaba S, Sud A, Mandlecha P, Goel L, Nayak M. Comparative study between staples and Eight Plate in the management of coronal plane deformities of the knee in skeletally immature children. J Child Orthop. 2016 Oct;10(5):429-37. Epub 2016 Jul 14.

41. Gottliebsen M, Rahbek O, Hvid I, Davidsen M, Hellfritzsch MB, Møller-Madsen B. Hemiepiphysiodesis: similar treatment time for tension-band plating and for stapling: a randomized clinical trial on guided growth for idiopathic genu valgum. Acta Orthop. 2013 Apr;84(2):202-6. Epub 2013 Mar 14.

42. Noonan KJ, Halanski MA, Leiferman E, Wilsman N. Growth retardation (hemiepiphyseal stapling) and growth acceleration (periosteal resection) as a method to improve guided growth in a lamb model. J Pediatr Orthop. 2016 Jun;36(4):362-9.

43. Hosseinzadeh P, Ross DR, Walker JL, Talwalkar VR, Iwinski HJ, Milbrandt TA. Three methods of guided growth for pediatric lower extremity angular deformity correction. Iowa Orthop J. 2016;36:123-7.

44. Boero S, Michelis MB, Riganti S. Use of the Eight-Plate for angular correction of knee deformities due to idiopathic and pathologic physis: initiating treatment according to etiology. J Child Orthop. 2011 Jun;5(3):209-16. Epub 2011 May 12.

45. Burghardt RD, Kanellopoulos AD, Herzenberg JE. A technical note on improved instrumentation for Blount staple insertion. J Child Orthop. 2012 Aug;6(4):347-50. Epub 2012 Aug 9.

46. Jelinek EM, Bittersohl B, Martiny F, Scharfstädt A, Krauspe R, Westhoff B. The 8-Plate versus physeal stapling for temporary hemiepiphyseodesis correcting genu valgum and genu varum: a retrospective analysis of thirty five patients. Int Orthop. 2012 Mar;36(3):599-605. Epub 2011 Oct 9.

47. Park SS, Kang S, Kim JY. Prediction of rebound phenomenon after removal of hemiepiphyseal staples in patients with idiopathic genu valgum deformity. Bone Joint J. 2016 Sep;98-B(9):1270-5.

48. Corominas-Frances L, Sanpera I, Saus-Sarrias C, Tejada-Gavela S, Sanpera-Iglesias J, Frontera-Juan G. Rebound growth after hemiepiphysiodesis: an animal-based experimental study of incidence and chronology. Bone Joint J. 2015 Jun;97-B(6):862-8.

49. Blount WP. A mature look at epiphyseal stapling. Clin Orthop Relat Res. 1971;77:158-63.

50. Stevens PM. The role of guided growth as it relates to limb lengthening. J Child Orthop. 2016 Dec;10(6):479-86. Epub 2016 Dec 2.

51. Cooper GA, Southorn T, Eastwood DM, Bache CE. Lower extremity deformity management in MPS IVA, Morquio-Brailsford syndrome: preliminary report of hemiepiphysiodesis correction of genu valgum. J Pediatr Orthop. 2016 Jun;36(4):376-81.

52. Ashby E, Eastwood D. Characterization of knee alignment in children with mucopolysaccharidosis types I and II and outcome of treatment with guided growth. J Child Orthop. 2015 Jun;9(3):227-33. Epub 2015 Jun 16.

53. Yilmaz G, Oto M, Thabet AM, Rogers KJ, Anticevic D, Thacker MM, Mackenzie WG. Correction of lower extremity angular deformities in skeletal dysplasia with hemiepiphysiodesis: a preliminary report. J Pediatr Orthop. 2014 Apr-May;34(3):336-45.

54. Pendleton AM, Stevens PM, Hung M. Guided growth for the treatment of moderate leg-length discrepancy. Orthopedics. 2013 May;36(5):e575-80.

55. Latalski M, Fatyga M, Kołtowski K, Menartowicz P, Repko M, Filipovič M. Guided-growth implants in the treatment of early onset scoliosis. A pilot study. Ortop Traumatol Rehabil. 2013 Jan-Feb;15(1):23-9.

56. Stevens PM, Kennedy JM, Hung M. Guided growth for ankle valgus. J Pediatr Orthop. 2011;31(8):878-83.

57. Stevens PM, Novais EN. Multilevel guided growth for hip and knee varus secondary to chondrodysplasia. J Pediatr Orthop. 2012 Sep;32(6):626-30.

58. Agus H, Önvural B, Kazimoglu C, Reisoglu A, Kalenderer O. Medial percutaneous hemi-epiphysiodesis improves the valgus tilt of the femoral head in developmental dysplasia of the hip (DDH) type-II avascular necrosis. Acta Orthop. 2015;86(4):506-10. Epub 2015 Apr 24.

59. Lee WC, Kao HK, Yang WE, Ho PC, Chang CH. Guided growth of the proximal femur for hip displacement in children with cerebral palsy. J Pediatr Orthop. 2016 Jul-Aug;36(5):511-5.

60. Spiro AS, Stenger P, Hoffmann M, Vettorazzi E, Babin K, Lipovac S, Kolb JP, Novo de Oliveira A, Rueger JM, Stuecker R. Treatment of fixed knee flexion deformity by anterior distal femoral stapling. Knee Surg Sports Traumatol Arthrosc. 2012 Dec;20(12):2413-8. Epub 2012 Feb 4.

61. Al-Aubaidi Z, Lundgaard B, Pedersen NW. Anterior distal femoral hemiepiphysiodesis in the treatment of fixed knee flexion contracture in neuromuscular patients. J Child Orthop. 2012 Aug;6(4):313-8. Epub 2012 Jul 14.

62. LaPorta GA, Susek MM. Guided growth with temporary hemiepiphysiodesis to treat ankle valgus in a skeletally immature individual: a case report. J Foot Ankle Surg. 2016 May-Jun;55(3):645-9. Epub 2015 Oct 1.

63. Davids JR, Valadie AL, Ferguson RL, Bray EW 3rd, Allen BL Jr. Surgical management of ankle valgus in children: use of a transphyseal medial malleolar screw. J Pediatr Orthop. 1997 Jan-Feb;17(1):3-8.

64. Stevens PM, Belle RM. Screw epiphysiodesis for ankle valgus. J Pediatr Orthop. 1997 Jan-Feb;17(1):9-12.

65. Driscoll MD, Linton J, Sullivan E, Scott A. Medial malleolar screw versus tension-band plate hemiepiphysiodesis for ankle valgus in the skeletally immature. J Pediatr Orthop. 2014 Jun;34(4):441-6.

66. Oda JE, Thacker MM. Distal tibial physeal bridge: a complication from a tension band plate and screw construct. Report of a case. J Pediatr Orthop B. 2013 May;22(3):259-63.

67. Fox IM, Smith SD. Juvenile bunion correction by epiphysiodesis of the first metatarsal. J Am Podiatry Assoc. 1983 Sep;73(9):448-55.

68. Seiberg M, Green R, Green D. Epiphysiodesis in juvenile hallux abducto valgus. A preliminary retrospective study. J Am Podiatr Med Assoc. 1994 May;84(5):225-36.

69. Arami A, Bar-On E, Herman A, Velkes S, Heller S. Guiding femoral rotational growth in an animal model. J Bone Joint Surg Am. 2013 Nov 20;95(22):2022-7.

70. Cullu E, Cobanoglu M, Peker MK. The effect of guided growth on rotational deformities of the long bones: a biomechanical study on Sawbone. Int J Pediatr Orthop. 2015;1(1):44-7.

71. Cobanoglu M, Cullu E, Kilimci FS, Ocal MK, Yaygingul R. Rotational deformities of the long bones can be corrected with rotationally guided growth during the growth phase. Acta Orthop. 2016 Jun;87(3):301-5. Epub 2016 Feb 22.

72. Dannawi Z, Altaf F, Harshavardhana NS, El Sebaie H, Noordeen H. Early results of a remotely-operated magnetic growth rod in early-onset scoliosis. Bone Joint J. 2013 Jan;95-B(1):75-80.

73. Latalski M, Fatyga M, Kołtowski K, Danielewicz-Bromberek A, Menarowicz P. Paper #2: Guided Growth System (GGS) in the treatment of early-onset scoliosis–5 years' follow-up. Spine Def.2(6):498-9.

74. Jain V, Lykissas M, Trobisch P, Wall EJ, Newton PO, Sturm PF, Cahill PJ, Bylski-Austrow DI. Surgical aspects of spinal growth modulation in scoliosis correction. Instr Course Lect. 2014;63:335-44.

75. Skaggs DL, Akbarnia BA, Flynn JM, Myung KS, Sponseller PD, Vitale MG; Chest Wall and Spine Deformity Study Group; Growing Spine Study Group; Pediatric Orthopaedic Society of North America; Scoliosis Research Society Growing Spine Study Committee. A classification of growth friendly spine implants. J Pediatr Orthop. 2014 Apr-May;34(3):260-74.

76. Yazici M, Olgun ZD. Growing rod concepts: state of the art. Eur Spine J. 2013 Mar;22(Suppl 2):S118-30. Epub 2012 May 8.

77. Burghardt RD, Specht SC, Herzenberg JE. Mechanical failures of Eight-Plate guided growth system for temporary hemiepiphysiodesis. J Pediatr Orthop. 2010 Sep;30(6):594-7.

78. Saran N, Rathjen KE. Guided growth for the correction of pediatric lower limb angular deformity. J Am Acad Orthop Surg. 2010 Sep;18(9):528-36.

79. Macwilliams BA, Harjinder B, Stevens PM. Guided growth for correction of knee flexion deformity: a series of four cases. Strategies Trauma Limb Reconstr. 2011 Aug;6(2):83-90. Epub 2011 Jul 22.

80. Rais Y, Reich A, Simsa-Maziel S, Moshe M, Idelevich A, Kfir T, Miosge N, Monsonego-Ornan E. The growth plate's response to load is partially mediated by mechano-sensing via the chondrocytic primary cilium. Cell Mol Life Sci. 2015 Feb;72(3):597-615. Epub 2014 Aug 2.

81. Rauch F. Bone growth in length and width: the yin and yang of bone stability. J Musculoskelet Neuronal Interact. 2005 Jul-Sep;5(3):194-201. Epub 2005 Sep 21.

82. Gkiatas I, Lykissas M, Kostas-Agnantis I, Korompilias A, Batistatou A, Beris A. Factors affecting bone growth. Am J Orthop (Belle Mead NJ). 2015 Feb;44(2):61-7.

83. Frost HM. Intermediary organization of the skeleton. Boca Raton, FL: CRC Press; 1986.

84. Anderson M, Green WT, Messner MB. Growth and predictions of growth in the lower extremities. J Bone Joint Surg Am. 1963 Jan;45:1-14.

85. Moseley CF. A straight-line graph for leg-length discrepancies. J Bone Joint Surg Am. 1977 Mar;59(2):174-9.

86. Paley D, Bhave A, Herzenberg JE, Bowen JR. Multiplier method for predicting limb-length discrepancy. J Bone Joint Surg Am. 2000 Oct;82(10):1432-46.

87. Staheli LT. Fundamentals of pediatric orthopedics. Wolters Kluwer Health/Lippincott Williams & Wilkins; 2008.

88. Little DG, Nigo L, Aiona MD. Deficiencies of current methods for the timing of epiphysiodesis. J Pediatr Orthop. 1996 Mar-Apr;16(2):173-9.

89. White GR, Mencio GA. Genu valgum in children: diagnostic and therapeutic alternatives. J Am Acad Orthop Surg. 1995 Oct;3(5):275-83.

90. Hansson LI, Zayer M. Physiological genu varum. Acta Orthop Scand. 1975 May;46(2):221-9.

91. Rozbruch SR, Fryman C, Schachter LF, Bigman D, Marx RG. Growth arrest of the tibia after anterior cruciate ligament reconstruction: lengthening and deformity correction with the Taylor Spatial Frame. Am J Sports Med. 2013 Jul;41(7):1636-41. Epub 2013 Apr 25.

92. Lombardo SJ, Harvey JP Jr. Fractures of the distal femoral epiphyses. Factors influencing prognosis: a review of thirty-four cases. J Bone Joint Surg Am. 1977 Sep;59(6):742-51.

93. Koman JD, Sanders JO. Valgus deformity after reconstruction of the anterior cruciate ligament in a skeletally immature patient. A case report. J Bone Joint Surg Am. 1999 May;81(5):711-5.

94. Jung ST, Park H, Lee JH, Kim JR. Residual angulation of distal tibial diaphyseal fractures in children younger than ten years. J Orthop Surg Res. 2014 Oct 9;9:84.

95. Cozen L. Fracture of the proximal portion of the tibia in children followed by valgus deformity. Surg Gynecol Obstet. 1953 Aug;97(2):183-8.

96. Denduluri SK, Lu M, Bielski RJ. Development of genu valgum after removal of osteochondromas from the proximal tibia. J Pediatr Orthop B. 2016 Nov;25(6):582-6.

97. Inan M, Thacker M, Church C, Miller F, Mackenzie WG, Conklin D. Dynamic lower extremity alignment in children with achondroplasia. J Pediatr Orthop. 2006 Jul-Aug;26(4):526-9.

98. Brooks WC, Gross RH. Genu varum in children: diagnosis and treatment. J Am Acad Orthop Surg. 1995 Nov;3(6):326-35.

99. Kumar A, Jain VK, Bharadwaj M, Arya RK. Ollier disease: pathogenesis, diagnosis, and management. Orthopedics. 2015 Jun;38(6):e497-506.

100. Gaebe G, Kruse R, Rogers K, Mackenzie WG, Holmes L Jr. Dynamic lower extremity deformity in children with pseudoachondroplasia. J Pediatr Orthop. 2016 Jun 13. [Epub ahead of print].

101. Nawata K, Teshima R, Minamizaki T, Yamamoto K. Knee deformities in multiple hereditary exostoses. A longitudinal radiographic study. Clin Orthop Relat Res. 1995 Apr;313:194-9.

102. Weiner DS, Tank JC, Jonah D, Morscher MA, Krahe A, Kopits S, Schrader WC. An operative approach to address severe genu valgum deformity in the Ellis-van Creveld syndrome. J Child Orthop. 2014 Feb;8(1):61-9. Epub 2014 Jan 25.

103. Odunusi E, Peters C, Krivit W, Ogilvie J. Genu valgum deformity in Hurler syndrome after hematopoietic stem cell transplantation: correction by surgical intervention. J Pediatr Orthop. 1999 Mar-Apr;19(2):270-4. Epub 1999 Mar 24.

104. Ravelli A, Martini A. Juvenile idiopathic arthritis. Lancet. 2007 Mar 3;369(9563):767-78.

105. Shultz SP, D'Hondt E, Fink PW, Lenoir M, Hills AP. The effects of pediatric obesity on dynamic joint malalignment during gait. Clin Biomech (Bristol, Avon). 2014 Aug;29(7):835-8. Epub 2014 May 21.

106. Wiemann JM 4th, Tryon C, Szalay EA. Physeal stapling versus 8-Plate hemiepiphysiodesis for guided correction of angular deformity about the knee. J Pediatr Orthop. 2009 Jul-Aug;29(5):481-5.

107. Gyr BM, Colmer HG 4th, Morel MM, Ferski GJ. Hemiepiphysiodesis for correction of angular deformity in pediatric amputees. J Pediatr Orthop. 2013 Oct-Nov;33(7):737-42.

108. Ballal MS, Bruce CE, Nayagam S. Correcting genu varum and genu valgum in children by guided growth: temporary hemiepiphysiodesis using tension band plates. J Bone Joint Surg Br. 2010 Feb;92(2):273-6.

109. Kanellopoulos AD, Mavrogenis AF, Dovris D, Vlasis K, Burghart R, Soucacos PN, Papagelopoulos PJ, Herzenberg JE. Temporary hemiepiphysiodesis with Blount staples and Eight-Plates in pigs. Orthopedics. 2011 Apr 11;34(4).

110. Heflin JA, Ford S, Stevens P. Guided growth for tibia vara (Blount's disease). Medicine (Baltimore). 2016 Oct;95(41):e4951.

111. Mielke CH, Stevens PM. Hemiepiphyseal stapling for knee deformities in children younger than 10 years: a preliminary report. J Pediatr Orthop. 1996 Jul-Aug;16(4):423-9.