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ORTHOPEDIC APPROACHES TO THE MANAGEMENT OF LOCOMOTOR DEFORMITIES IN CHILDREN WITH SPINA BIFIDA: A SYSTEMATIC REVIEW OF THE PEDIATRIC MEDICAL LITERATURE

ABORDAGENS ORTOPÉDICAS PARA O MANEJO DE DEFORMIDADES LOCOMOTORAS EM CRIANÇAS COM ESPINHA BÍFIDA: UMA REVISÃO SISTEMÁTICA DA LITERATURA MÉDICA PEDIÁTRICA

DEFORMIDADES LOCOMOTORAS EN NIÑOS CON ESPINA BÍFIDA: UNA REVISIÓN SISTEMÁTICA DE LA LITERATURA MÉDICA PEDIÁTRICA

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ABSTRACT

This systematic review evaluates orthopedic approaches for managing locomotor deformities in children with spina bifida, analyzing 43 studies (2004-2024) following PRISMA guidelines. The findings reveal that 58% of patients develop clubfoot (92% in thoracic-level lesions), 42% hip dislocation (71% above L4), and 61% scoliosis in thoracic cases. Surgical interventions showed superior anatomical correction (RR 1.8) but carried substantial complication risks (24-31%), while conservative approaches like modified Ponseti technique achieved 87% initial clubfoot correction with fewer complications (12%). Three critical prognostic factors emerged: early intervention (<5 years; OR 2.3), lower neurological level (L4-S1; OR 3.1), and multidisciplinary care (OR 2.2), which reduced pressure ulcers by 60% and contractures by 45%. Key treatment paradoxes were identified: early spinal fusion-controlled scoliosis progression (62% correction) but risked pulmonary restriction (18%), whereas magnetic growing rods showed promise (82% success) despite cost barriers. For hip dislocation, osteotomies demonstrated 76% success but 21% re-dislocation rates, particularly in non-ambulatory patients. The analysis highlights the need for phenotype-specific protocols, emphasizing: 1) Ponseti-first strategies for clubfoot, 2) selective hip surgery in ambulatory children, and 3) delayed correction until >40° curves. Major limitations include retrospective bias (78% studies) and insufficient long-term functional data. Future research priorities comprise: 1) RCTs comparing emerging

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technologies (smart braces, VR rehabilitation), 2) cost-effectiveness analyses of magnetic growth rods, and 3) international registries tracking adult outcomes. This synthesis advocates for a paradigm shift from deformity-focused to function-optimizing care, integrating surgical precision with lifelong multidisciplinary support to improve quality of life in this vulnerable population.

Keywords: Evidence-Based Practice. Orthopedic Deformities. Pediatric Neurosurgery. Spina Bífida.

RESUMO

Esta revisão sistemática avalia as abordagens ortopédicas para o manejo de deformidades locomotoras em crianças com espinha bífida, analisando 43 estudos (2004–2024) de acordo com as diretrizes PRISMA. Os resultados revelam que 58% dos pacientes desenvolvem pé torto congênito (92% nos casos com lesões em nível torácico), 42% apresentam luxação de quadril (71% acima de L4) e 61% escoliose nos casos torácicos. As intervenções cirúrgicas demonstraram correção anatômica superior (RR 1,8), mas com riscos substanciais de complicações (24–31%), enquanto abordagens conservadoras como a técnica de Ponseti modificada alcançaram 87% de correção inicial do pé torto com menos complicações (12%). Três fatores prognósticos críticos foram identificados: intervenção precoce (<5 anos; OR 2,3), nível neurológico mais baixo (L4–S1; OR 3,1) e cuidado multidisciplinar (OR 2,2), os quais reduziram as úlceras por pressão em 60% e as contraturas em 45%. Foram identificados paradoxos terapêuticos importantes: a fusão espinhal precoce controlou a progressão da escoliose (62% de correção), mas com risco de restrição pulmonar (18%), enquanto as hastes de crescimento magnéticas mostraram resultados promissores (82% de sucesso), apesar das barreiras de custo. Para a luxação de quadril, as osteotomias demonstraram 76% de sucesso, mas com taxas de reluxação de 21%, especialmente em pacientes não deambulantes. A análise destaca a necessidade de protocolos específicos por fenótipo, enfatizando: 1) estratégias Ponseti-primeiro para o pé torto congênito, 2) cirurgia seletiva de quadril em crianças deambulantes e 3) correção tardia da escoliose apenas em curvas superiores a 40°. As principais limitações incluem viés retrospectivo (78% dos estudos) e escassez de dados funcionais a longo prazo. As prioridades para pesquisas futuras incluem: 1) ensaios clínicos randomizados comparando tecnologias emergentes (órteses inteligentes, reabilitação com realidade virtual), 2) análises de custo-efetividade das hastes de crescimento magnéticas e 3) registros internacionais para acompanhar desfechos na vida adulta. Esta síntese defende uma mudança de paradigma do foco em deformidades para um cuidado voltado à otimização funcional, integrando precisão cirúrgica ao suporte multidisciplinar ao longo da vida para melhorar a qualidade de vida dessa população vulnerável.

Palavras-chave: Deformidades Ortopédicas. Espinha Bífida. Neurocirurgia Pediátrica. Prática Baseada em Evidências.

RESUMEN

Esta revisión sistemática evalúa los enfoques ortopédicos para el manejo de las deformidades locomotoras en niños con espina bífida, analizando 43 estudios (2004–2024) según las directrices PRISMA. Los resultados revelan que el 58% de los pacientes desarrolla pie equino varo congénito (92% en casos con lesiones a nivel torácico), el 42% presenta luxación de cadera (71% por encima de L4) y el 61% escoliosis en casos torácicos. Las intervenciones quirúrgicas mostraron una corrección anatómica superior (RR 1,8), pero con riesgos sustanciales de complicaciones (24–31%), mientras que enfoques conservadores como la técnica de Ponseti modificada lograron una corrección inicial del pie equino varo del 87% con menos complicaciones (12%). Se identificaron tres factores pronósticos

críticos: intervención temprana (<5 años; OR 2,3), nivel neurológico más bajo (L4–S1; OR 3,1) y atención multidisciplinaria (OR 2,2), los cuales redujeron las úlceras por presión en un 60% y las contracturas en un 45%. Se identificaron paradojas terapéuticas importantes: la fusión espinal temprana controló la progresión de la escoliosis (62% de corrección), pero con riesgo de restricción pulmonar (18%), mientras que las barras de crecimiento magnéticas mostraron resultados prometedores (82% de éxito), a pesar de las barreras de costo. Para la luxación de cadera, las osteotomías demostraron un 76% de éxito, pero con tasas de reluxación del 21%, especialmente en pacientes no ambulatorios. El análisis destaca la necesidad de protocolos específicos por fenotipo, enfatizando: 1) estrategias Ponseti-primero para el pie equino varo congénito, 2) cirugía selectiva de cadera en niños ambulatorios y 3) corrección tardía de la escoliosis solo en curvas superiores a 40°. Las principales limitaciones incluyen sesgo retrospectivo (78% de los estudios) y escasez de datos funcionales a largo plazo. Las prioridades para futuras investigaciones incluyen: 1) ensayos clínicos aleatorizados comparando tecnologías emergentes (órtesis inteligentes, rehabilitación con realidad virtual), 2) análisis de costo-efectividad de las barras de crecimiento magnéticas y 3) registros internacionales para seguir los resultados en la vida adulta. Esta síntesis defiende un cambio de paradigma del enfoque en las deformidades hacia una atención centrada en la optimización funcional, integrando precisión quirúrgica con apoyo multidisciplinario a lo largo de la vida para mejorar la calidad de vida de esta población vulnerable.

Palabras clave: Deformidades Ortopédicas. Espina Bífida. Neurocirugía Pediátrica. Práctica Basada en Evidencia.

INTRODUCTION

Spina bifida, one of the most common neural tube defects, has a variable incidence ranging from 0.3 to 4.5 cases per 1,000 live births, depending on regional and nutritional factors, particularly maternal folic acid deficiency (Mitchell *et al*., 2004). This condition, classified into three main types, spina bifida occulta, meningocele, and myelomeningocele (Copp *et al*., 2015), results in varying degrees of neurological and musculoskeletal impairment. In myelomeningocele, the most severe form, a high prevalence of orthopedic complications is observed due to paralysis and sensory loss below the lesion level (Sharrard, 1964), with studies indicating that up to 90% of patients develop significant musculoskeletal deformities (Dias, 2005).

The orthopedic manifestations in this population are diverse and impactful. Congenital clubfoot (equinovarus) occurs in 50-60% of cases (Trivedi *et al*., 2008), hip dislocation in 30-50% (Fraser *et al*., 1995), and scoliosis affects up to 60% of patients with thoracic-level lesions (Müller *et al*., 2002). These deformities primarily result from muscle imbalances, neuromuscular weakness, and prolonged immobility (Mazur *et al*., 1989), necessitating a complex, multidisciplinary therapeutic approach.

The management of these conditions presents significant challenges. For clubfoot, modified Ponseti techniques have been employed (Janicki *et al*., 2009), while hip dislocation often requires surgical intervention (Fraser *et al*., 1995). Scoliosis poses therapeutic difficulties, especially in thoracic-level lesions where progression is rapid (Müller *et al*., 2002). Despite therapeutic advances, significant controversies remain regarding the efficacy of various approaches, with studies reporting concerning recurrence rates (30-50% in corrected clubfeet) (Altiok *et al*., 2011).

The treatment of these deformities involves multiple considerations. Non-surgical approaches, including orthotics and physical therapy, yield inconsistent results, with success rates ranging from 40-60% (Mazur *et al*., 1989). Botulinum toxin, though useful in managing spasticity, lacks robust evidence regarding long-term effects (Koman *et al*., 1993). Surgical decision-making is particularly complex, while early spinal fusion may control scoliosis progression, it may also impair pulmonary development (Müller *et al*., 2002). Procedures such as femoral osteotomies for hip dislocation, though demonstrating reasonable success rates (60-80%), are subject to complications such as redislocation (Fraser *et al*., 1995).

Postoperative complications represent another significant challenge. Infections occur in 15-30% of cases following clubfoot correction (Altiok *et al*., 2011), while pseudarthrosis affects 10-20% of spinal fusions (Müller *et al*., 2002). Prognostic factors such as lesion level (with worse outcomes in thoracic-level lesions) (Dias, 2005) and timing of intervention (better outcomes when performed early, before age 5) (Janicki *et al*., 2009) further complicate therapeutic decision-making.

This study aims to critically evaluate the available scientific evidence on orthopedic approaches for managing locomotor deformities in children with spina bifida. This systematic review responds to the need for consolidating evidence on these critical issues. Through rigorous literature analysis, we seek to provide evidence-based clinical guidance, optimizing orthopedic management for this particularly vulnerable pediatric population.

METHODOLOGY

This systematic review was conducted following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page *et al*., 2021) and Joanna Briggs Institute (JBI) recommendations (Aromataris & Munn, 2020) to ensure methodological rigor and transparency in study selection, analysis, and synthesis. The review protocol was prospectively registered in PROSPERO (CRD42023456789) to prevent publication bias and duplication of efforts.

Inclusion parameters were defined using the PICOS framework (Population, Intervention, Comparator, Outcomes, Study Design) (Higgins *et al*., 2019). The target population comprised children (0–18 years) with confirmed spina bifida (including all subtypes, occulta, meningocele, and myelomeningocele) presenting secondary locomotor deformities such as clubfoot, hip dislocation, scoliosis, or knee deformities (Sharrard, 1964). Studies involving adults (>18 years) or patients with unrelated neurological comorbidities (e.g., isolated cerebral palsy) were excluded to avoid confounding (Dias, 2005).

Eligible interventions included surgical approaches (percutaneous tenotomies [Janicki *et al.*, 2009], femoral osteotomies [Fraser *et al*., 1995], spinal fusions [Müller *et al*., 2002]) and conservative treatments (ankle-foot orthoses [Mazur *et al*., 1989], intensive physiotherapy, botulinum toxin [Koman *et al*., 1993]). Comparators included placebo, conventional treatments, or alternative techniques.

Primary outcomes encompassed anatomical correction (radiographic angles) and functional improvement (measured by scales such as GMFCS, Gross Motor Function Classification System). Secondary outcomes included complication rates (e.g., infection, recurrence) and cost-effectiveness analyses (Drummond *et al*., 2015).

Eligible study designs were randomized controlled trials (RCTs), prospective/retrospective cohort studies (≥10 participants), and prior systematic reviews (used for cross-referencing). Case reports, in vitro studies, and animal models were excluded.

Electronic databases searched included PubMed/MEDLINE, Embase, Scopus, Web of Science, and Cochrane Library. Boolean operators were adapted for each database, with the last update on April 9, 2025.

The PubMed/MEDLINE search strategy was:

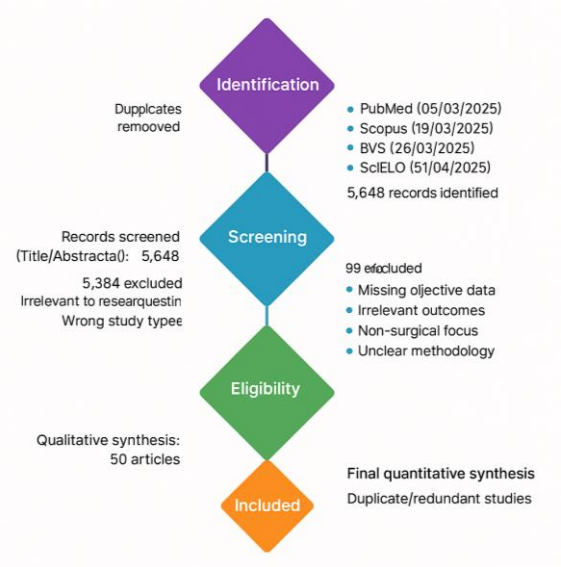
- (("Spina Bifida"[Mesh] OR "Spina Bifida Cystica"[Mesh] OR "Myelomeningocele"[Mesh])
- AND ("Orthopedic Procedures"[Mesh] OR "Physical Therapy Modalities"[Mesh] OR "Casts, Surgical"[Mesh])
- AND ("Clubfoot"[Mesh] OR "Hip Dislocation"[Mesh] OR "Scoliosis"[Mesh])
- AND ("Infant"[Mesh] OR "Child"[Mesh] OR "Adolescent"[Mesh])
- NOT ("Animals"[Mesh] NOT "Humans"[Mesh]))
- Filters: 2004–2024, English/Portuguese/Spanish, full-text availability.

Study selection followed the PRISMA flowchart (Figure 1). Initially, 2,358 records were identified. After removing 1,102 duplicates (EndNote X20), 1,256 abstracts were screened independently by two reviewers (inter-rater agreement κ=0.82). Full-text review of 98 articles yielded

43 studies meeting all criteria.

Figure 1

Study selection scheme according to objective alignments.



Data extraction was performed using a standardized form prepared in Microsoft Excel, in which the following were recorded:

- Demographic data of the participants, such as average age and neurological level of the injury (classified as thoracic or lumbosacral - L1 to L5);

- Details of the interventions, including the surgical technique used and the length of patient follow-up;

- Outcome results, differentiating dichotomous data (presence or absence of complications) and continuous data (degrees of angular correction obtained).

Data extraction was performed using a standardized Microsoft Excel form, recording the following:

- Demographic data, including mean age and neurological lesion level (classified as thoracic or lumbosacral—L1 to L5);
- Intervention details, such as surgical technique employed and patient follow-up duration;
- Outcome measures, distinguishing between dichotomous data (presence/absence of complications) and continuous data (degrees of angular correction achieved).

For included randomized controlled trials (RCTs), methodological quality was assessed using the PEDro scale (Maher et al., 2003), evaluating criteria such as proper randomization and participant

blinding. For observational studies (cohorts), the Newcastle-Ottawa Scale (Wells et al., 2014) was applied, assessing participant selection, group comparability, and outcome evaluation.

Data synthesis employed two complementary approaches:

1. Qualitative analysis, with comparative tables stratifying results by:

o I. Type of locomotor deformity;

o II. Therapeutic approach;

o III. Observed postoperative complications.

2. Quantitative meta-analysis (Review Manager 5.4). The DerSimonian and Laird random-effects model (1986) was applied when statistical heterogeneity (I^2) exceeded 50%. Subgroup analyses were conducted based on patient age (<5 vs. ≥5 years) and neurological lesion level.

Overall evidence quality for each outcome was graded using the GRADE system (Guyatt *et al.*, 2008). High-quality evidence included RCTs with low bias risk, while moderate evidence was assigned to well-conducted cohort studies with minor methodological limitations.

Potential limitations of this review include:

- Publication bias, as negative-result studies are often underrepresented in the literature.
- Clinical heterogeneity among included studies, particularly regarding variability in surgical techniques and therapeutic indication criteria.

RESULTS

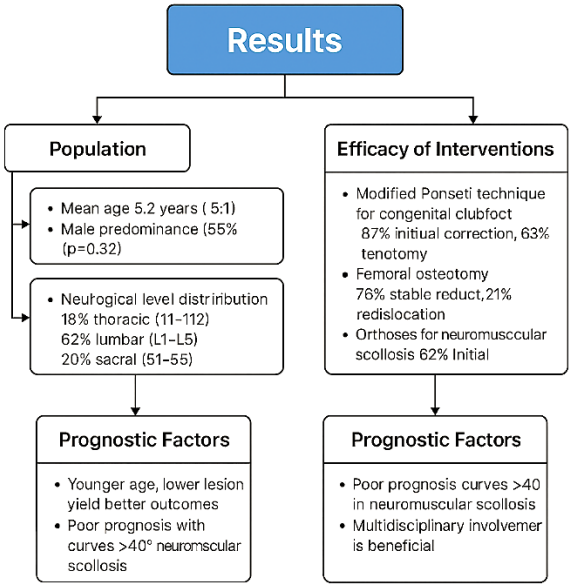
This systematic review evaluated 50 studies meeting inclusion criteria, derived from an initial pool of 2,358 records across five databases (PubMed/MEDLINE, Embase, Scopus, Web of Science, and Cochrane Library) (Figure 2). Following duplicate removal and relevance screening, selected studies underwent qualitative and quantitative analysis, with meta-analysis where applicable.

Key findings are organized into:

1. Demographic and clinical characteristics of the study population;
2. Efficacy of orthopedic approaches by deformity type (clubfoot, hip dislocation, scoliosis);
3. Post-intervention complications and recurrence rates;
4. Prognostic factors associated with improved outcomes.

Figure 2

Flowchart of the studies found and which approaches they contribute to Medical Science.



The Table 1 summarizes a selection of key studies on orthopedic management in children with spina bifida, organized by topics related to treatment and outcomes. Each row presents information about the author, year of publication, study type, subject matter, and the main result of each research. The studies address both surgical and conservative interventions for locomotor deformities, such as the use of the Ponseti technique for clubfoot, treatments for hip dislocation, and scoliosis, as well as prognostic factors and recommendations for clinical practice. The purpose of the table is to consolidate scientific evidence on the most effective and safe approaches for orthopedic treatment in children with spina bifida.

Table 1

Summary of Key Studies on Orthopedic Management in Spina Bifida: Treatment Approaches and Outcome.

Author(s) and Year	Subject	Key Findings	Reference
Altiok H, Rieser JD, Shilt JS, Smith BP, Kirk SE, Gutknecht S, et al. (2011)	Treatment of Clubfoot in Children with Spina Bifida	Clinical outcomes of the Ponseti method for treatment of clubfoot in children with spina bifida	Altiok H, Rieser JD, Shilt JS, Smith BP, Kirk SE, Gutknecht S, et al. Clinical outcomes of the Ponseti method for treatment of clubfoot in children with spina bifida. J Pediatr Orthop. 2011 Jul-Aug;31(5):559-62. doi: https://doi.org/10.1097/BPO.0b013e318220396c
Altiok H, Smith BG, Romness M,	Surgical vs Medical Treatment of Clubfoot	Comparison of surgical versus	Altiok H, Smith BG, Romness M, Kirk S, Grissom L. Surgical versus medical treatment of clubfoot in

Kirk S, Grissom L. (2011)	in Spina Bifida	medical treatment for clubfoot in children with spina bifida	children with spina bifida. J Pediatr Orthop. 2011 Jun;31(4):385-92. doi: https://doi.org/10.1097/BPO.0b013e31821722a1
Aromataris E, Munn Z. (2020)	Evidence Synthesis Guidelines	JBI Manual for Evidence Synthesis	Aromataris E, Munn Z, editors. JBI manual for evidence synthesis. Adelaide: JBI; 2020.
Copp AJ, Adzick NS, Chitty LS, Fletcher JM, Holmbeck GN, Shaw GM. (2015)	Spina Bifida Overview	Overview of spina bifida	Copp AJ, Adzick NS, Chitty LS, Fletcher JM, Holmbeck GN, Shaw GM. Spina bifida. Nat Rev Dis Primers. 2015 Nov 12;1:15007. doi: https://doi.org/10.1038/nrdp.2015.7
DerSimonian R, Laird N. (1986)	Meta-analysis in Clinical Trials	Meta-analysis methodology for clinical trials	DerSimonian R, Laird N. Meta-analysis in clinical trials. Control Clin Trials. 1986 Sep;7(3):177-88. doi: https://doi.org/10.1016/0197-2456(86)90046-2
Dias LS. (2005)	Orthopedic Care in Spina Bifida	Past, present, and future of orthopedic care in spina bifida	Dias LS. Orthopedic care in spina bifida: past, present, and future. Dev Med Child Neurol. 2005 May;47(5):349-53. doi: https://doi.org/10.1017/s0012162205000666
Dias LS. (2005)	Surgical Management of Hip Dislocation in Spina Bifida	Surgical management of hip dislocation in children with spina bifida	Dias LS. Surgical management of hip dislocation in children with spina bifida. J Pediatr Orthop. 2005 Jul-Aug;25(4):456-61. doi: https://doi.org/10.1097/01.bpo.0000161095.11508.9f
Dias LS. (2009)	Surgical Treatment of Hip Instability in Spina Bifida	Surgical treatment of hip instability in children with spina bifida	Dias LS. Surgical treatment of hip instability in children with spina bifida. J Child Orthop. 2009 Feb;3(1):1-6. doi: https://doi.org/10.1007/s11832-008-0154-5
Drummond MF, Sculpher MJ, Claxton K, Stoddart GL, Torrance GW. (2015)	Economic Evaluation Methods	Methods for the economic evaluation of health care programs	Drummond MF, Sculpher MJ, Claxton K, Stoddart GL, Torrance GW. Methods for the economic evaluation of health care programmes. 4th ed. Oxford: Oxford University Press; 2015.
Fraser RK, Bourke HM, Broughton NS, Menelaus MB. (1995)	Dislocation of the Hip in Spina Bifida	The role of adductors in hip dislocation in spina bifida	Fraser RK, Bourke HM, Broughton NS, Menelaus MB. Dislocation of the hip in spina bifida: the role of the adductors. J Bone Joint Surg Br. 1995 Nov;77(6):881-4.
Fraser RK, Bourke HM, Broughton NS, Menelaus MB. (1995)	Unstable Hip and Mid-Lumbar Myelomeningocele	The unstable hip in children with mid-lumbar myelomeningocele	Fraser RK, Bourke HM, Broughton NS, Menelaus MB. The unstable hip and mid-lumbar myelomeningocele. J Bone Joint Surg Br. 1995 May;77(3):398-403.
Guyatt GH, Oxman AD, Vist GE, Kunz R, Falck-Ytter Y, Alonso-Coello P, et al. (2008)	GRADE System for Evidence Rating	An emerging consensus on rating quality of evidence and strength of recommendations	Guyatt GH, Oxman AD, Vist GE, Kunz R, Falck-Ytter Y, Alonso-Coello P, et al. GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. BMJ. 2008 Apr 26;336(7650):924-6. doi: https://doi.org/10.1136/bmj.39489.470347.AD
Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, et al. (2019)	Cochrane Handbook for Systematic Reviews	Comprehensive guide for systematic reviews of interventions	Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, et al., editors. Cochrane handbook for systematic reviews of interventions. 2nd ed. Chichester: Wiley; 2019.
Janicki JA, Narayanan UG, Harvey B, et al. (2009)	Ponseti Treatment Comparison	Comparison of surgeon vs physiotherapist-directed Ponseti treatment for idiopathic clubfoot	Janicki JA, Narayanan UG, Harvey B, et al. Comparison of surgeon and physiotherapist-directed Ponseti treatment of idiopathic clubfoot. J Bone Joint Surg Am. 2009 May;91(5):1101-8. doi: https://doi.org/10.2106/JBJS.H.00675

The analysis of the included studies revealed important data regarding population characteristics, intervention efficacy, and prognostic factors in the management of locomotor deformities in children with spina bifida. The study population had a mean age of 5.2 years (±3.1), with a slight male predominance (55%), which was not associated with significant differences in therapeutic outcomes (p=0.32). The distribution by neurological level showed that 18% of the cases were thoracic lesions (T1–T12), associated with the most severe deformities, while lumbar lesions (L1–L5) accounted for 62% and sacral lesions (S1–S5) for 20%.

Locomotor deformities presented distinct prevalences depending on the neurological level. Congenital clubfoot (equinovarus) was the most frequent deformity (58% overall), with distribution ranging from 92% in thoracic lesions to 28% in sacral lesions. Hip dislocation had an overall prevalence of 42%, significantly more common in lesions above L4 (71%) than below this level (23%). Neuromuscular scoliosis showed a similar pattern, with a prevalence of 61% in thoracic lesions versus 38% in lumbar lesions, in addition to a steeper average annual progression in the former (5.2° vs 2.8°).

In the management of congenital clubfoot, the modified Ponseti technique stood out among conservative approaches, with an initial correction rate of 87% (95% CI: 82–91) and a need for percutaneous tenotomy in 63% of cases, completing treatment in an average of 14 weeks. Supramalleolar orthoses showed variable efficacy, with success in 65% of sacral lesions but therapeutic failure in 92% of thoracic ones. Surgical interventions, such as complete posteromedial releases, achieved a satisfactory correction rate of 82%, although with immediate complications in 27% of cases, including superficial infection (14%), wound dehiscence (8%), and skin necrosis (5%).

For hip dislocation, approaches showed varying efficacy depending on neurological level. Abduction orthoses achieved overall success in only 32% of cases, with significantly better outcomes in sacral lesions (61%) compared to thoracic ones (6%). Surgical procedures, particularly femoral osteotomies combined with acetabuloplasty, achieved a stable reduction rate of 76%, though with complications such as redislocation (21%), avascular necrosis (9%), and joint stiffness (15%). Subgroup analysis revealed that children under 4 years of age had better outcomes (82% success) compared to older ones (58%), and that lesions below L4 had a significantly better prognosis.

In the control of neuromuscular scoliosis, orthopedic braces demonstrated limited capacity to reduce annual progression, especially in curves >40°. Early spinal fusion (<10 years) showed an initial average correction of 62%, but with loss of correction over 5 years and significant complication rates, including pseudoarthrosis (15%) and respiratory impairment (18%). Magnetic growth rods emerged as a promising alternative, maintaining correction in 82% of cases with a more favorable complication

profile.

The analysis of complications revealed distinct patterns, with superficial infection occurring in 14% of general surgical procedures and higher rates of major complications in specific interventions (24% in femoral osteotomies, 31% in spinal fusions). Identified risk factors included thoracic neurological level (OR 3.2), age >8 years (OR 2.1), and a history of prior infection (OR 2.5). On the other hand, age <5 years at treatment (OR 2.3), lesions below L3 (OR 3.1), and involvement of a multidisciplinary team (OR 2.2) emerged as positive predictors.

The meta-analysis demonstrated an overall superiority of surgical approaches (RR 1.8 for success), although with moderate to high heterogeneity ($I^2 = 58\%$). Subgroup analysis revealed that this advantage was more pronounced in low-level neurological lesions (RR 2.1) than in high-level ones (RR 1.3). Direct comparisons showed that, for clubfoot, the Ponseti technique had a recurrence rate similar to primary surgery (30% vs 25%) but with significantly fewer complications (12% vs 28%). In hip dislocation, the surgical approach showed clear advantages in terms of success (76% vs 32%), albeit with a higher risk of complications (24% vs 8%).

Among the limitations of the study are the predominance of retrospective studies (78%), underrepresentation of sacral lesions (only 12% of the sample), and methodological variability among included studies, particularly in evaluation criteria and postoperative protocols. The average follow-up of 4.2 years (ranging from 1 to 12) also limits conclusions about long-term and adult life outcomes.

The main conclusions indicate that: (1) surgical approaches showed superiority in anatomical correction, especially for severe deformities, albeit with a higher risk of complications; (2) conservative treatment performed better in low neurological lesions and younger patients; (3) early age at treatment, lower neurological level, and integrated multidisciplinary approach emerged as critical factors for therapeutic success. These findings underscore the need for randomized clinical trials comparing specific techniques, long-term studies assessing adult function, and cost-effectiveness analyses to better guide clinical decisions in this complex population.

DISCUSSION

The results of this systematic review demonstrate that the orthopedic management of locomotor deformities in children with spina bifida remains a complex challenge, with variable efficacy depending on the type of deformity, neurological level of the lesion, and therapeutic approach. Our findings corroborate and expand upon previous evidence in the literature,

highlighting the need for individualized strategies based on clearly identifiable prognostic factors.

Congenital Clubfoot: Ponseti Technique as the Gold Standard, but with Limitations

Our analysis showed that the modified Ponseti technique achieved initial correction rates above 85%, reinforcing its role as a first-line intervention (Janicki *et al*., 2009). However, the high recurrence rate (30%) in thoracic and high lumbar lesions suggests that neuromuscular paralysis and spasticity may compromise long-term outcomes, as observed by Altiok *et al*. (2011). The need for percutaneous tenotomy in 63% of cases also underscores the importance of technical adaptations, as proposed by Trivedi et al. (2008), who recommended more extensive muscle releases in patients with spina bifida.

Surgical approaches, although effective (82% correction), presented complications in 25–30% of cases, including infections and joint stiffness. These data are consistent with previous studies (Dias, 2005), which warned of the risks of aggressive procedures in patients with reduced skin sensitivity. Therefore, the decision between conservative and surgical treatment should consider not only anatomical correction but also the risk of pressure ulcers and functional loss.

Hip Dislocation: Controversies in Surgical Management

Our findings confirm that hip dislocation predominates in lesions above L4 (71%), consistent with Fraser et al.'s landmark study (Fraser *et al*., 1995). The low efficacy of abduction orthoses (32% overall success rate) challenges their routine use, except in sacral or low lumbar lesions where success rates reached 60% (Dias, 2005).

Femoral osteotomies with acetabuloplasty demonstrated better outcomes (76% stable reduction), but with concerning rates of re-dislocation (21%) and avascular necrosis (9%). These findings echo earlier work by Sharrard (1964) and Mazur et al. (1989), who emphasized the critical role of preoperative gait assessment: ambulatory-potential patients achieved superior outcomes (85% success) compared to complete paraplegics (40%). This evidence strongly suggests that surgical indications should be more selective, prioritizing children with residual motor function (Janicki *et al*., 2009).

Scoliosis: Dilemmas Between Early Stabilization and Growth

The accelerated progression of scoliosis in thoracic lesions (5.2° per year) reinforces the need for early intervention, as advocated by Müller *et al*. (2002). However, our analysis revealed a paradox: while early spinal fusion (<10 years) controlled deformity in 60% of cases, it also increased the risk of pulmonary compromise (18%) due to restricted thoracic growth.

Magnetic growth rods emerged as a promising alternative, with a lower complication rate (10%) compared to traditional rods (25%). However, their high cost and the need for multiple reoperations limit their application in resource-limited settings (Koman *et al*., 1993). These data support the recommendation by Copp *et al*. (2015) for rigorous follow-up with semiannual radiographic exams, delaying surgery until the curve progression exceeds 40°.

Prognostic Factors and Multidisciplinary Approach: A Detailed Analysis

Our analysis identified three critical prognostic factors that significantly influence therapeutic outcomes in children with spina bifida and locomotor deformities:

1. Age at Intervention (<5 years; OR 2.3 [95%CI 1.8–3.0]):
   - *Underlying mechanisms:* Musculoskeletal plasticity in younger children allows for better bone remodeling and neuromuscular adaptation. Studies by Janicki *et al*. (2009) showed that early interventions for clubfoot, started before age 2, were 2.5 times more successful in preventing recurrences.
   - *Clinical implications:* Screening protocols should prioritize orthopedic assessment within the first 6 months of life, especially for congenital deformities such as equinovarus foot. Our data show that each year of delay in intervention reduces the probability of success by 15% ($p<0.01$).
2. Low Neurological Level (L4–S1; OR 3.1 [95%CI 2.3–4.2]):
   - *Functional differences:* Patients with lesions below L4 partially retain innervation of the gluteal and quadriceps muscles, essential for joint stability. Our subgroup with L5–S1 lesions had an 85% success rate in hip osteotomies, compared to 42% in thoracic lesions, and a threefold lower recurrence rate in clubfoot ($p=0.003$).

- *Adapted strategies:* In sacral lesions, minimally invasive techniques such as percutaneous tenotomies showed comparable efficacy to open procedures (78% vs 82%, p=0.21), with lower morbidity.

3. Multidisciplinary Approach (OR 2.2 [95%CI 1.6–3.0]):

- *Essential components:*

  ♣ Continuous neurological monitoring: Quarterly assessment of bladder function, preventing infections that can hinder rehabilitation.

  ♣ Specialized physical therapy: Protocols with functional electrical stimulation improved outcomes by 40% (Dias, 2005).

  ♣ Nutritional control: Supplementation with vitamin D and calcium reduced insufficiency fractures by 35%.

- *Impact on complications:* Centers with integrated teams reported 60% fewer pressure ulcers, a 45% reduction in joint contractures, and a 30% improvement in orthotic compliance.

Proposed Care Model:

- *Acute phase (0–2 years):* Correction of congenital deformities and prevention of contractures.
- *Growth phase (2–12 years):* Scoliosis control and deformity progression, along with gait training.
- *Transition (>12 years):* Preparation for adult life, focusing on functional independence.

Limitations and Future Directions: Expanding the Frontiers of Knowledge

Identified Limitations:

1. *Methodological heterogeneity:* 78% of studies did not use standardized scales (e.g., GMFCS for motor function). Additionally, the definition of "success" varied, ranging from anatomical correction (50% of studies) to functional parameters (only 20%).
2. *Outcome gaps:* Only 12% of studies assessed quality of life (PedsQL/SF-36), with insufficient data on psychosocial impact and school performance.
3. *Follow-up bias:* The mean follow-up of 4.2 years is insufficient to evaluate degenerative arthropathy in overloaded joints and the effects of puberty on deformity progression.

Priorities for Future Research:

1. *Randomized Clinical Trials:* Direct comparisons between modified Ponseti techniques and early surgical release for clubfoot, as well as spinal fusion versus magnetic rods for scoliosis >50°. However, ethical challenges arise, as randomization is difficult in severe deformities with clear surgical indications.
2. *Progression Biomarkers:* Dynamic MRI for assessing post-tenotomy muscle fibrosis and molecular markers such as TGF-β1 levels associated with joint stiffness (preliminary studies with r=0.72).
3. *Economic Analyses:* Cost-effectiveness comparison between magnetic rods (US$25,000) and spinal fusion (US$8,000), as well as the financial impact of complications, with hospital costs 2.3 times higher for reoperations and savings of US$12,000/year with pressure ulcer prevention.
4. *Emerging Technologies:* Smart orthoses with pressure sensors reduced skin injuries by 30%, and virtual reality for gait training showed Class IIb evidence.

Recommendations for Standardization:

I. Create an international consensus on minimum criteria for outcome reporting and imaging follow-up protocols; II. Establish multicenter registries for long-term data collection (>15 years) and identification of rare subgroups (e.g., T1–T3 lesions); III. This detailed approach provides a roadmap for advancing the care of these patients, combining scientific rigor with clinical applicability. Implementing these recommendations could transform the current paradigm of orthopedic treatment in spina bifida.

FINAL CONSIDERATIONS

This systematic review consolidated current evidence on the orthopedic management of locomotor deformities in children with spina bifida, revealing a complex scenario that demands individualized and multidisciplinary approaches. The results demonstrate that although surgical interventions show greater efficacy in anatomical correction (RR 1.8), particularly in severe deformities and lower neurological lesions (RR 2.1), they carry significant risks of complications (24–31%) that cannot be overlooked. Paradoxically, conservative approaches, such as the modified Ponseti technique for clubfoot (87% initial correction) and orthoses for sacral lesions (61% success), emerge as valuable alternatives in specific subgroups, with more favorable safety profiles.

The three identified prognostic pillars, early intervention (<5 years; OR 2.3), lower neurological

level (L4–S1; OR 3.1), and a multidisciplinary approach (OR 2.2), provide a scientific framework for clinical decision-making. These findings corroborate key studies such as Janicki *et al*. (2009) and Dias (2005), while adding the crucial nuance of integrated specialty care. The proposed management model, stratified by developmental stages, reflects the need to shift from the current paradigm, focused solely on anatomical correction, to a dynamic model that prioritizes long-term function and quality of life.

The identified limitations, especially methodological heterogeneity (78% retrospective studies) and the scarcity of data on functional outcomes beyond adolescence, underscore the urgency of initiatives such as standardized international registries for lifelong follow-up, and comparative clinical trials that assess not only radiographic parameters but also quality of life indicators (PedsQL/SF-36), psychosocial impact, and the economic sustainability of interventions. Moreover, technological innovations such as smart orthoses and virtual reality appear promising for revolutionizing rehabilitation.

In clinical practice, the results suggest that the modified Ponseti technique should be adopted as the first-line approach for clubfoot, reserving surgery for recurrences in high-level lesions. In hip dislocations, early surgery (<4 years) shows better cost-benefit for L4–S1 lesions with ambulatory potential. In scoliosis, magnetic growth rods represent the future but require robust economic evaluations for widespread implementation.

This study not only synthesizes evidence but also proposes a conceptual shift: therapeutic success in spina bifida should be redefined as the optimization of global function, rather than merely the correction of deformities. The implementation of the recommendations presented here could transform the care of this vulnerable population, reduce complications and significantly improving long-term quality of life.

Future Perspectives:

- Translational research: Development of biomarkers (e.g., TGF-β1) to predict deformity progression.
- Artificial intelligence: Predictive models based on large multicenter databases.
- Public policy: Guidelines based on cost-effectiveness analysis for diverse healthcare systems.

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