

1917 2017



RHODE ISLAND MEDICAL JOURNAL



SPECIAL SECTION
PEDIATRIC REHABILITATION MEDICINE (PRM)

GUEST EDITOR: JON A. MUKAND, MD, PhD



J. Mukand, MD

**16 Pediatric Rehabilitation Medicine (PRM):
An Integrative Approach to Identifying and Treating
Congenital and Childhood Disabilities**

JON A. MUKAND, MD, PhD
GUEST EDITOR



J. Raducha, MD



B. Cohen, MD

**17 A Review of Brachial Plexus Birth
Palsy: Injury and Rehabilitation**

JEREMY E. RADUCHA, MD
BRIAN COHEN, MD
TRAVIS BLOOD, MD
JULIA KATARINCIC, MD



T. Blood, MD



J. Katarincic, MD

**21 The Role of Rehabilitation in
the Management of Adolescent
Idiopathic Scoliosis**

JOSE M. RAMIREZ, MD
CRAIG P. EBERSON, MD



J. Ramirez, MD



C. Ebersson, MD

**26 Pediatric Anterior Cruciate
Ligament Rehabilitation:
A Review**

STEVEN F. DEFRODA, MD, MEng
KATHRYN HILLER, BS
ARISTIDES I. CRUZ, Jr., MD, MB



S. DeFroda, MD



A. Cruz, MD



PHOTOS COURTESY OF THE SARGENT REHABILITATION CENTER

Students Boris Franz (cover photo) and Billy Naughton (above) are shown participating in the pediatric physical therapy program, one of the many therapeutic, diagnostic and evaluation services offered at the Sargent Rehabilitation Center (sargentcenter.org) in Warwick, RI.

Pediatric Rehabilitation Medicine (PRM): An Integrative Approach to Identifying and Treating Congenital and Childhood Disabilities

JON A. MUKAND, MD, PhD

GUEST EDITOR

Pediatric Rehabilitation Medicine (PRM) is a challenging and rewarding sub-specialty of Rehabilitation Medicine. The American Board of Physical Medicine & Rehabilitation defines it as “the subspecialty that uses an interdisciplinary approach to address the prevention, diagnosis, treatment, and management of congenital and childhood-onset physical impairments including related or secondary medical, physical, functional, psychosocial, cognitive, and vocational limitations or conditions, with an understanding of the life course of disability.”¹

Children are vulnerable to disabling conditions starting before birth (e.g. toxoplasmosis), at birth (e.g. hypoxic-ischemic encephalopathy), and through the adolescent phase (e.g. injuries). CDC data (2015) on injury deaths are a useful index for disabilities among the survivors of those injuries.² For the two decades between ages 5–24, motor vehicle collisions were the most common cause of death. Suicide by firearms was the third (n = 139) most common cause for ages 10–14 and the fourth (n = 2,461) for ages 15–24. Even for young people, there is a risk of homicide by firearms: it was the second most common cause of death (n = 4,140) for the age group of 15–24. Some of the injuries that afflict children every day could be prevented by education from medical practitioners, for instance, advising parents to secure guns in safes and to ensure safe seating in cars.

This issue of the *Rhode Island Medical Journal* features the intersection of orthopedic surgery and rehabilitation for the pediatric population. Pediatric surgery requires a clear understanding of the natural course of pathologic conditions, the nature of pediatric tissue healing, the developmental process, and psychosocial issues.

Brachial plexus injuries at birth occur in up to fifty children in Rhode Island annually. They require the surgeon to be patient and wait for the natural recovery process, to enlist occupational therapists for rehabilitation, and to carefully select a small percentage of infants for surgery. At a later stage of life, children may have to contend with adolescent idiopathic scoliosis. Fortunately, only 10% of these children require surgical intervention. Sports injuries are relatively common in America. About half of injuries that eventually lead to surgery involve the knee, and in 25% of these cases the anterior cruciate ligament is injured. The most vulnerable athletes are 16-year-old females and 17-year-old males. All three of these conditions are discussed in this special issue, in articles that are authored by orthopedic surgery residents and co-authored by their attending physicians at Rhode Island Hospital. As a rehabilitation physician, I appreciated these articles for their accessibility and usefulness for general medical practitioners, and I hope that the readership of the journal will also benefit from them.

References

1. <https://www.abpmr.org/Subspecialties/PRM>, Accessed 10/7/17
2. https://www.cdc.gov/injury/images/lc-charts/leading_causes_of_injury_deaths_unintentional_injury_2015_1050w760h.gif, Accessed 10/7/17

Guest Editor

Jon A. Mukand, MD, PhD, is Consulting Medical Director, Southern New England Rehabilitation Center; Medical Director, Sargent Rehabilitation Center; Clinical Assistant Professor, Rehabilitation Medicine, Brown University, Tufts University.

A Review of Brachial Plexus Birth Palsy: Injury and Rehabilitation

JEREMY E. RADUCHA, MD; BRIAN COHEN, MD; TRAVIS BLOOD, MD; JULIA KATARINCIC, MD

ABSTRACT

Brachial plexus injuries during the birthing process can leave infants with upper extremity deficits corresponding to the location of the lesion within the complex plexus anatomy. Manifestations can range from mild injuries with complete resolution to severe and permanent disability. Overall, patients have a high rate of spontaneous recovery (66–92%).^{1,2} Initially, all lesions are managed with passive range motion and observation. Prevention and/or correction of contractures with occupational therapy and serial splinting/casting along with encouraging normal development are the main goals of non-operative treatment. Surgical intervention may be warranted, depending on functional recovery.

KEYWORDS: Brachial plexus, Erb's palsy, Klumpke's palsy, serial splinting

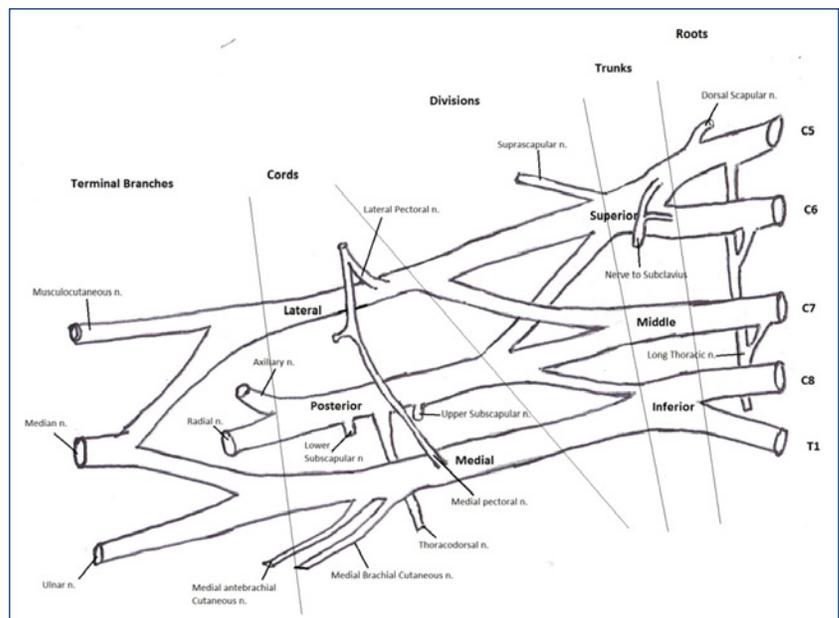
INTRODUCTION

Brachial plexus birth palsy (BPBP) involves injury to any nerve of the brachial plexus during birth. It occurs in 0.42 to 4.6 cases per 1,000 births, which translates to approximately 5 to 50 cases per year in Rhode Island, with varying degrees of severity.^{1–3} The most common presentation is Erb's Palsy (50–60%), followed by the more severe upper plexus and pan-plexus variants.^{1,4} Klumpke's lower plexus palsy is rare, and occurs in 0.6% of all patients.⁵ Maternal risk factors include gestational diabetes, multi-parity and having a previous child with a brachial plexus injury. Maternal factors can cause fetal macrosomia and/or shoulder dystocia, increasing the risk of forceps or suction-assisted deliveries and traction nerve injury.⁶ Since the majority of fetuses present in the left occiput anterior position, with the right shoulder under the maternal pelvis, the right upper extremity is most commonly involved.⁷ However, only about half of patients have these risk factors, demonstrating our lack of true understanding of the etiology.⁸ This article will review the pathology, diagnosis, treatment, rehabilitation and outcomes of BPBP.

ANATOMY

The brachial plexus is derived from the fifth cervical (C5) to the first thoracic (T1) nerve roots. It undergoes a complex pattern of branching and convergence before terminating as peripheral nerves that provide motor and sensory innervation to the upper extremity. (Figure 1, Table 1) The plexus can be divided into supraclavicular (roots and trunks) and sub-clavicular (cords and terminal branches) for prognostic purposes, with supraclavicular injuries having worse outcomes.⁹

Figure 1. Brachial Plexus Anatomy



Pathophysiology

The majority of BPPBs are traction injuries, as with shoulder dystocia when traction on the infant's neck leads to an increased neck shoulder angle.¹ Very rarely, compression injuries from fractured clavicles, hematomas, and pseudoaneurysm can occur.⁷ Lesions can be divided into symptomatic categories using multiple systems. The simplest approach is to classify lesions as pre-ganglionic or post-ganglionic, distal to the dorsal root ganglion. Pre-ganglionic lesions, with the nerve injured proximally, e.g., root avulsions, are more difficult to heal/repair and have worse outcomes than post-ganglionic lesions. It is only possible to determine this

Table 1. Brachial Plexus Functions

Branching Location	Nerve	Root	Innervation	Muscle action
Roots	Dorsal Scapular n.	C5	M: Rhomboid mm. and Levator Scapulae m.	Rhom: scapular retraction, Levator=scapular elevation
	Long Thoracic n.	C5,C6 & C7	M: Serratus anterior m.	Scapular protraction
	First intercostal n.	T1	M: intercostal m.	n/a
Trunks	Suprascapular n.	C5, C6	M: Supraspinatus m, Infraspinatus m. S: Shoulder joint capsule	Supra= Arm abduction. Infra= Arm external rotation
	Nerve to Subclavius	C5, C6	M: Subclavius m.	n/a
Divisions	none			
Cords				
Posterior	Upper Subscapular n	C5-T1	<i>Motor:</i> Upper subscapularis m.	Arm internal rotation
	Lower Subscapular n	C5-T1	<i>Motor:</i> Lower Subscapularis m., Teres Major m.	LS= Arm internal rotation
	Thoracodorsal n.	C5-T1	<i>Motor:</i> Latissimus dorsi m.	Arm adduction
Lateral	Lateral Pectoral n.	C5-C7	<i>Motor:</i> Pectoralis Major m.	Arm Adduction
Medial	Medial Pectoral n.	C8-T1	<i>Motor:</i> Pectoralis Major m., Pectoralis Minor m.	Arm Adduction
	Medial Brachial cutaneous n.	C8-T1	<i>Sensory:</i> medial arm	n/a
	Medial Antebrachial cutaneous n.	C8-T1	<i>Sensory:</i> medial forearm	n/a
Terminal Nerves	Radial n.	C5-T1	<i>Motor:</i> Triceps mm, brachioradialis m., ECRL, ECRB, ECU, EDC, EIP, EDM, EPL, EPB, APL, Supinator m., Finger extensors <i>Sensory:</i> posterior brachial cutaneous, inferior lateral brachial cutaneous, posterior antebrachial cutaneous, superficial radial (post. radial hand)	Elbow extension, Wrist extension, Finger Extension, Thumb extension, thumb abduction, Forearm supination; Brachioradialis=elbow flexion
	Axillary n.	C5-T1	<i>Motor:</i> Deltoid m., Teres Minor m., <i>Sensory:</i> Lateral proximal arm	Delt= Arm abduction, Teres= Arm external rotation
	Musculocutaneous n.	C5-C7	<i>Motor:</i> Biceps brachii m., Brachialis m, coracobrachialis m. <i>Sensory:</i> Lateral cutaneous n. of the forearm	Elbow Flexion, Forearm supination S: lateral forearm
	Median n.	C5-T1	<i>Motor:</i> FCR, Palmaris longus m., FDS, radial 1/2 FDP, Pronator teres m. FPL, Pronator quadratus m., FPB (superficial head), Opponens pollicis, APB, 1st-2nd lumbricals <i>Sensory:</i> Radial 3 1/2 fingers, palmar cutaneous branch	Wrist flexion, Forearm pronation, thumb flexion/abduction/opposition, finger PIP flexion, IF/MF MCP and DIP flexion
	Ulnar n.	C8-T1	<i>Motor:</i> FCU, ulnar 1/2 FDP, Flexor DM, Abductor DM, Opponens DM, Adductor pollicis, FPB (deep head), Palmaris brevis m. Dorsal interossei mm. Palmar interossei mm., 3rd-4th Lumbricals <i>Sensory:</i> Dorsal ulnar cutaneous n., Palmar ulnar cutaneous n.	Wrist flexion, Thumb adduction/flexion, SF flexion/abduction/opposition, finger adduction/abduction, 4th and 5th finger DIP/MCP flexion

classification after advanced imaging. The Sunderland classification (Table 2) categorizes nerve injuries based on the nerve structures damaged, ranging in severity from neuropraxia to neurotmesis.¹⁰ As expected, patients with less severe damage, e.g., neuropraxia, have a better chance at recovery.

The most common way to describe BPPBs is based on the nerve roots involved, which can be detected by physical examination. Upper trunk (Erb-Duchenne) palsies involve only the disruption of input from the C5 and C6 nerve roots. Upper plexus palsies involve roots C5, C6 and C7, with the addition of more distal deficits. Lower plexus (Klumpke's) palsies involve the C8 and T1 nerve roots and can also affect the sympathetic chain with pre-ganglionic injuries. The most severe is the all-encompassing pan-plexus injury involving nerve roots C5-T1, with disruption to all functions of the upper extremity.

Table 2. Sunderland Classification

	Type of Nerve Injury	Prognosis
Neuropraxia	Stretch injury with intact nerve continuity	Spontaneous recovery likely
Axonotmesis	Axonal injury with intact nerve sheath	Variable recovery
Neurotmesis	Complete nerve rupture; neither axon nor sheath intact	Poor prognosis for spontaneous recovery

Sunderland SS. The anatomy and physiology of nerve injury. *Muscle Nerve*. 1990;13(9):771-784. doi:10.1002/mus.880130903

DIAGNOSIS

Maternal history, physical examination and diagnostic imaging can provide a wealth of information to make the proper diagnosis and injury classification. The patient's mother should be interviewed for the BPBP risk factors mentioned previously. Abnormal primitive reflexes, e.g., Moro reflex and tonic neck reflex, are often the first clues in the newborn examination. It is also important to palpate the infant's clavicle and humerus, as fractures can affect upper extremity movements and be confused with brachial plexus palsy. A septic shoulder and isolated radial nerve palsy should also be in the differential diagnosis, but they are less common and are associated with different physical and laboratory findings.

Depending where the lesion is located, the patient's affected extremity will present in different positions. With Erb's palsy (C5-6), the arm is adducted and internally rotated at the shoulder and extended at the elbow, due to weakness in the deltoid, supero-posterior rotator cuff and biceps. A patient with upper plexus palsy (C5-7) has the above posture as well as wrist and fingers flexion due to radial nerve involvement and wrist/finger extensor weakness. Pan-plexus injuries (C5-T1) typically present with a flaccid extremity. Pre-ganglionic injuries, which carry a worse prognosis, may lead to head tilting to the opposite side (denervation of paraspinal musculature), medial winging of the scapula, diaphragm dysfunction, and Horner's syndrome.

As children age, their disabilities become more apparent. Scoring systems such as the Toronto Test Score, Active Movement Scale, and Modified Mallet system have been developed to grade and track upper extremity function.¹¹ The Modified Mallet score is the most commonly used when evaluating older children (≥ 3 years old). It uses five categories to assess shoulder function, with a 0–5 grading for each category. Higher scores correlate to higher function, but the examination requires patient participation and is heavily weighted toward shoulder external rotation.

Imaging can help clarify the diagnosis and classification. Initially, radiographs of the upper extremity should be obtained to rule out fractures, which could be confused with or occur concomitantly with brachial plexus palsy. MRI and CT myelography can be used to detect root avulsions. Electromyography has been suggested if there is no nerve recovery by 6 months of age, in order to detect a pre-ganglionic injury, which is potentially amenable to operative intervention. Other evidence shows, however, that electromyography can be discordant from clinical bicep function at 3 months of age and the test may not be a reliable indicator for surgery.¹

TREATMENT AND OUTCOMES

Treatment for a suspected brachial plexus palsy should begin immediately with frequent, passive range of motion of the affected upper extremity. Parents should be instructed to range both arms at every diaper change to make it a daily routine and encourage compliance. Some authors recommend a

two-week period of immobilization to promote healing and decrease pain,⁹ but others find little evidence that immobilization has any benefit.¹ Contractures can begin as early as 2-3 weeks after birth, with the glenohumeral joint most commonly affected. Without early treatment, the contractures can progress rapidly and cause posterior subluxation/dislocation of the humeral head.^{1,9,12}

After an initial observation period, children can be categorized as having either partial or total paralysis. Patients with total paralysis should be referred to a tertiary center for early surgical evaluation, as they have a very low likelihood of spontaneous recovery. Patients with partial paralysis have a higher chance of recovery, and there is complete recovery by 3 months of age with as many as 92% of these patients.^{9,13} Other evidence suggests complete recovery rates may not be as high as originally thought, with as many as 20–30% of patients having a long-term deficit.^{1,2} Patients who do not have complete recovery by 1 month of age should be evaluated by a pediatric therapist for continued monitoring and rehabilitation. Many physicians use the lack of antigravity biceps function return by 3 months as an indication for nerve surgery since it is a poor prognostic indicator for complete spontaneous recovery,^{1,4} however, this does not preclude good functional recovery. Recovery of wrist extension is also a positive prognostic sign. Other physicians advocate continued rehabilitation until at least 6 months of age before considering surgery. Some evidence has shown that children who recovered antigravity biceps function between the 3rd and 6th months of life always had an incomplete recovery compared to those who regained function prior to 3 months.⁹

If children undergo surgery, it is typically performed between 3 and 8 months of age; earlier surgery (at 3 months) is indicated in children with pan-plexus palsies and Horner's syndrome. The main goals of surgery, in order of importance, are to restore elbow flexion, shoulder abduction, shoulder external rotation, wrist extension and hand function.⁷ The options for early surgical intervention include direct nerve repair with resection and grafting, or nerve transfers from surrounding motor nerves. In spite of surgery, many patients still suffer some degree of long-term sequelae.² In patients who develop contracture or have persistent weakness, later surgery can be beneficial. Lysis of contractures, osteotomies and local tendon transfers can help return functional motion and correct deformities.^{12,14}

Children who recover meaningful biceps function by 6 months of age are typically treated non-operatively with rehabilitation and monitoring. There is little high grade research discussing non-operative management techniques and protocols for brachial plexus birth palsies. All non-operative treatment involves a multidisciplinary team approach, with occupational therapy and splinting to prevent or correct contractures. The goals of treatment prior to muscle function recovery are to prevent contracture, strengthen recovering muscles, stimulate sensory nerves, and encourage the achievement of normal developmental milestones. As the

child grows, passive range of motion should be transitioned to participation in age-appropriate activities for rehabilitation with regular follow-up to assess functional scores, arm growth and joint integrity. Elbow flexion contractures are a fairly common occurrence, even with triceps sparing palsies. For children who develop contractures, stretching and serial night splinting can be used for contractures less than 20 degrees. Treating deformities in this range will prevent progression and help cosmetic appearance, as the elbow's functional range of motion is between 30–130 degrees.¹⁵ Serial casting and splinting of elbow flexion contractures can yield good results, but this approach can be complicated by radial head dislocation, bony ingrowth at the joint, and loss of elbow flexion while gaining extension. Much of the research is focused on elbow flexion contractures but contractures preventing forearm supination and shoulder external rotation are also commonly present. A pilot study has shown improvement in Toronto and Active Movement Scales of supination and shoulder external rotation with a Supination-External rotation orthosis worn 22 hours per day with relievers for therapy twice per day.¹⁶ Botulinum toxin injections with serial casting have also shown promise in patients who failed serial casting alone.¹⁷ The toxin relaxes the antagonist muscle at the contracted joint, particularly in cases of co-contraction, a common long-term complication.

Despite the lack of consensus regarding surgical indications and rehabilitation protocols, patients do have good long-term outcomes. Most studies show the majority of patients are independent in activities of daily living, even with persistent functional deficits.^{1,2,7,8,13,19} In a subjective study of adolescents, all patients reported a 'really good' quality of life, but they were also all dissatisfied with their current condition and hoped for continued improvement.²⁰

CONCLUSION

Brachial plexus birth palsies can be stressful and challenging for parents and children. Despite a better understanding of the pathology and treatment options, injury incidence has remained unchanged.¹⁻³ In general, upper plexus palsies recover better than lower plexus and pan-plexus palsies; neuropraxia does better than neurotmesis; and post-ganglionic lesions recover better than pre-ganglionic lesions. Care should continue to focus on early identification and therapy to minimize complications. Early referral to tertiary centers is crucial, as a multi-disciplinary approach can help promote recovery and prevent complication. Fortunately there is a high rate of spontaneous recovery, but for patients who don't recover spontaneously there are non-surgical and surgical options to improve functional outcomes and prevent devastating contractures. With an ever-expanding body of research geared towards improving care and knowledge of the injury, the future should show improved long-term outcomes for these patients.

References

1. Malessy MJA, Pondaag W. Obstetric Brachial Plexus Injuries. *Neurosurg Clin N Am.* 2009;20(1):1-14. doi:10.1016/j.nec.2008.07.024.
2. Hoeksma AF, Wolf H, Oei SL. Obstetrical brachial plexus injuries: incidence, natural course and shoulder contracture. *Clin Rehabil.* 2000;14(5):523-526. doi:10.1191/0269215500cr3410a.
3. Evans-Jones G, Kay SPJ, Weindling AM, et al. Congenital brachial palsy: incidence, causes, and outcome in the United Kingdom and Republic of Ireland. *Arch Dis Child Fetal Neonatal Ed.* 2003;88(3):F185-9. <http://www.ncbi.nlm.nih.gov/pubmed/12719390>. Accessed May 15, 2017.
4. Kozin SH. Brachial Plexus Microsurgical Indications. *J Pediatr Orthop.* 2010;30:S49-S52. doi:10.1097/BPO.0b013e3181cd9ed2.
5. al-Qattan MM, Clarke HM, Curtis CG. Klumpke's birth palsy. Does it really exist? *J Hand Surg Br.* 1995;20(1):19-23. <http://www.ncbi.nlm.nih.gov/pubmed/7759926>. Accessed May 15, 2017.
6. Gilbert WM, Nesbitt TS, Danielsen B. Associated factors in 1611 cases of brachial plexus injury. *Obstet Gynecol.* 1999;93(4):536-540. <http://www.ncbi.nlm.nih.gov/pubmed/10214829>. Accessed May 15, 2017.
7. Shenaq SM, Bullocks JM, Dhillon G, Lee RT, Laurent JP. Management of infant brachial plexus injuries. *Clin Plast Surg.* 2005;32(1):79-98. doi:10.1016/j.cps.2004.09.001.
8. Hale HB, Bae DS, Waters PM. Current concepts in the management of brachial plexus birth palsy. *J Hand Surg Am.* 2010;35(2):322-331. doi:10.1016/j.jhsa.2009.11.026.
9. Abid A. Brachial plexus birth palsy: Management during the first year of life. *Orthop Traumatol Surg Res.* 2016;102(1 Suppl):S125-32. doi:10.1016/j.otsr.2015.05.008.
10. Sunderland SS. The anatomy and physiology of nerve injury. *Muscle Nerve.* 1990;13(9):771-784. doi:10.1002/mus.880130903.
11. Duff S, DeMatteo C. Clinical Assessment of the Infant and Child Following Perinatal Brachial Plexus Injury. *J Hand Ther.* 2015;28(2):126-134. doi:10.1016/j.jht.2015.01.001.
12. Abid A, Accadbled F, Louis D, et al. Arthroscopic release for shoulder internal rotation contracture secondary to brachial plexus birth palsy: clinical and magnetic resonance imaging results on glenohumeral dysplasia. *J Pediatr Orthop B.* 2012;21(4):305-309. doi:10.1097/BPB.0b013e328353688e.
13. Laurent JP, Lee R, Shenaq S, Parke JT, Solis IS, Kowalik L. Neurosurgical correction of upper brachial plexus birth injuries. *J Neurosurg.* 1993;79(2):197-203. doi:10.3171/jns.1993.79.2.0197.
14. Abzug JM, Kozin SH. Evaluation and Management of Brachial Plexus Birth Palsy. *Orthop Clin North Am.* 2014;45(2):225-232. doi:10.1016/j.ocl.2013.12.004.
15. Ho ES, Roy T, Stephens D, Clarke HM. Serial casting and splinting of elbow contractures in children with obstetric brachial plexus palsy. *J Hand Surg Am.* 2010;35(1):84-91. doi:10.1016/j.jhsa.2009.09.014.
16. Durlacher KM, Bellows D, Verchere C. Sup-ER orthosis: an innovative treatment for infants with birth related brachial plexus injury. *J Hand Ther.* 2014;27(4):335-39; quiz 340. doi:10.1016/j.jht.2014.06.001.
17. Basciani M, Intiso D. Botulinum toxin type-A and plaster cast treatment in children with upper brachial plexus palsy. *Pediatr Rehabil.* 2006;9(2):165-170. doi:10.1080/13693780500402229.
18. Kerr C, McDowell B, Cosgrove A, Walsh D, Bradbury I, McDonough S. Electrical stimulation in cerebral palsy: a randomized controlled trial. *Dev Med Child Neurol.* 2006;48(11):870-876. doi:10.1017/S0012162206001915.
19. DiTaranto P, Campagna L, Price AE, Grossman JAI. Outcome following nonoperative treatment of brachial plexus birth injuries. *J Child Neurol.* 2004;19(2):87-90. doi:10.1177/08830738040190020101.
20. Squitieri L, Larson BP, Chang KWC, Yang LJS, Chung KC. Understanding quality of life and patient expectations among adolescents with neonatal brachial plexus palsy: a qualitative and quantitative pilot study. *J Hand Surg Am.* 2013;38(12):2387-2397.e2. <http://www.ncbi.nlm.nih.gov/pubmed/24416766>. Accessed May 8, 2017.

Authors

Jeremy E. Raducha, MD; Department of Orthopaedic Surgery,
Warren Alpert Medical School of Brown University,
Providence, RI.

Brian Cohen, MD; Department of Orthopaedic Surgery, Warren
Alpert Medical School of Brown University, Providence, RI.

Travis Blood, MD; Department of Orthopaedic Surgery, Warren
Alpert Medical School of Brown University, Providence, RI.

Julia Katarincic, MD; Department of Orthopaedic Surgery, Warren
Alpert Medical School of Brown University, Providence, RI.

Correspondence

Jeremy E. Raducha, MD
Department of Orthopaedic Surgery
Rhode Island Hospital
593 Eddy Street
Providence, RI 02903
401-444-4030
Fax 401-444-6182
Jeremy.raducha@gmail.com

The Role of Rehabilitation in the Management of Adolescent Idiopathic Scoliosis

JOSE M. RAMIREZ, MD; CRAIG P. EBERSON, MD

ABSTRACT

Adolescent idiopathic scoliosis (AIS) is a common clinical entity that affects approximately 2–3% of children and adolescents. AIS is defined as a curvature of the spine > 10 degrees and it usually presents as a right thoracic curve. Only a small fraction of patients with AIS go on to surgical intervention. This article will review the role of rehabilitation in the management of adolescent idiopathic scoliosis, specifically as related to the preoperative, perioperative and postoperative care of patients with AIS.

additional treatment option. The aim of these interventions is to slow or reverse deformity in the spine. Posterior spinal fusion (PSF) (**Figure 1**) is often indicated for patients who fail these conservative measures and progress to curves greater than 45 degrees with substantial skeletal growth remaining, as well as for patients with curves greater than 50 degrees.

Preoperative Considerations

Exercise therapy may improve an imbalance of peri-spinal musculature that is seen in AIS patients with small curves (< 20 degrees).^{15,16,18} This therapy may also be used a complement to bracing therapy in patients with larger curves. A study by Ko et al¹⁵ recently analyzed the effects of a 12-week

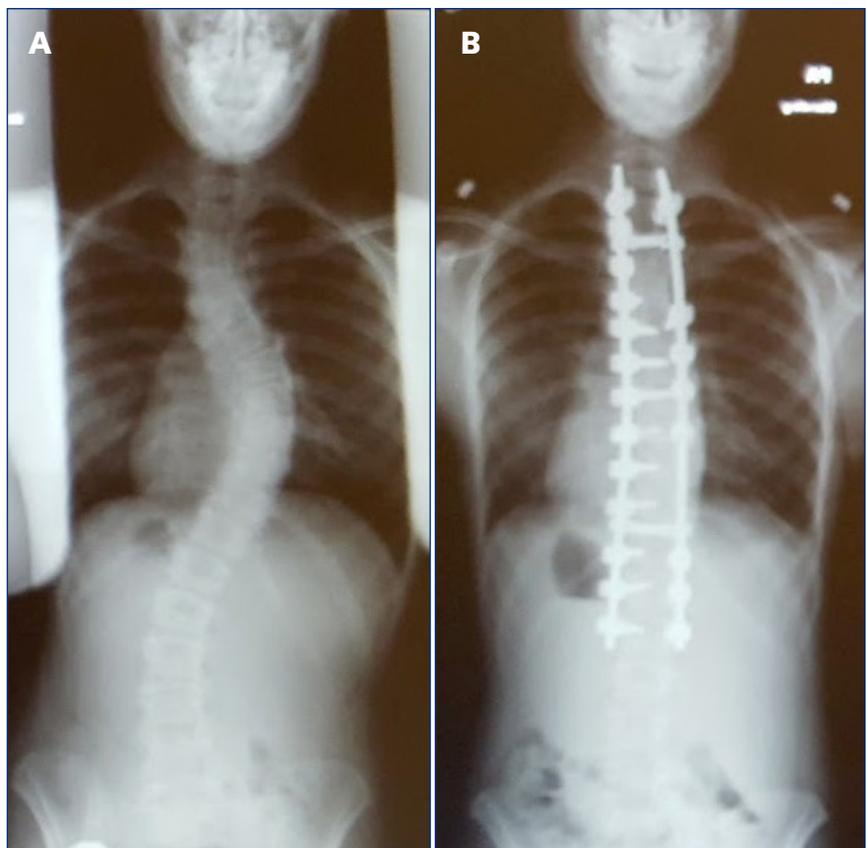
INTRODUCTION

Adolescent idiopathic scoliosis (AIS) is a common clinical entity that affects approximately 2–3% of children and adolescents. AIS is defined as a curvature of the spine > 10 degrees and it usually presents as a right thoracic curve. Only 10% of patients with AIS go on to surgical intervention.^{14,1}

The exact pathogenesis of AIS is not yet known. Multiple genetic and environmental factors have been implicated and continue to be the subject of intense research. Lifestyle factors have been implicated in the progression of AIS, but a recent, large cross-sectional study of over 2,700 female high school students failed to show any factors that were significantly related to AIS.¹³

The management of AIS is guided by curve magnitude and remaining skeletal growth. Rehabilitation plays an important and complementary role in the management of patients with AIS across the entire continuum of care. AIS patients with curves less than 25 degrees are typically observed and may be prescribed physical therapy in the form of scoliosis-specific exercises (SSE). Patients with curves between 25–45 degrees are often braced, with consideration of SSE as an

Figure 1. Thirteen-year-old patient initially treated with bracing and SSE for idiopathic scoliosis. She was poorly compliant and required surgery. Postoperatively, she returned to competitive swimming after 6 months, **A.** Preoperative anteroposterior image, **B.** Postoperative image.



core stabilization program on patients with AIS and curves of 10–20 degrees; there was a significant decrease in lumbar curve magnitudes in the treated groups. Gür et al¹⁷ similarly showed significant improvement in lumbar curve levels in patients undergoing a core stabilization exercise program. Moreover, a 2015 meta-analysis¹⁹ found moderate-quality evidence supporting the role of exercise therapy in modifying curve values, thoracic kyphosis trunk rotation, and quality of life in patients with AIS.

The increasingly popular Schroth rehabilitation program utilizes specific postures to correct scoliosis. A randomized clinical trial showed significantly improved curve magnitude as measured by Cobb angle and trunk rotation.²³ Similarly, active self-correction and task-oriented exercises have also been shown to be effective in achieving Cobb angle improvement (greater than 5 degrees) in a randomized clinical trial.²⁴ While by no means a panacea to AIS, postural rehabilitation and active self-correction rehabilitation programs should be considered for the management of AIS. Patient compliance and follow-through with the home portion of the program is imperative for success. Longer-term studies to evaluate these exercise interventions are ongoing and will determine the usefulness of these interventions.

Perioperative Considerations

For patients with progressive deformity, surgery heralds the beginning of an intensive rehabilitation period. The primary goal of inpatient rehabilitation after PSF is to ensure a safe home discharge. Doing so requires the coordinated effort of medical, nursing, and rehabilitation providers.

Medical priorities in the postoperative period include: monitoring the patient's hemodynamic status; achieving adequate pain control; managing the surgical site and various lines/drains (i.e., intravenous, bladder catheter); and ensuring normal bodily functions such as voiding.

Physical and occupational therapy goals include mobilizing the patient out of bed, ambulating on flat ground, navigating stairs, and performing activities of daily living in a safe manner. A survey of Shriners Hospital surgeons found the following physical therapy goals: Sitting on day 1, standing on day 2 and walking on day 2 or 3.¹²

Recently, care pathways have been developed to standardize and improve the postoperative rehabilitation of patients undergoing PSF for AIS. These pathways are designed to achieve a safe and efficient discharge to home after surgery. Fletcher et al⁶ reported the outcomes of one such pathway as it compared to traditional discharge planning. Both groups had a small difference in thoracolumbar curve Cobb values (35 degree in accelerated pathway vs. 40 degrees in traditional pathway), but there was no difference in proximal and main thoracic curve dimensions. As part of the accelerated discharge pathway, patients underwent aggressive postoperative rehabilitation with 2 to 3 sessions daily. Patients were transitioned to a regular diet on postoperative day 1,

at which time they were started on a multimodal regimen of oral analgesics and diazepam. Bladder catheters were removed on postoperative day 1 and surgical drains removed on day 1 or 2. Finally, patients were discharged to home with a standard bowel regimen if they were tolerating a regular diet, even if they did not yet have a bowel movement post-operatively. This study found a significantly shorter hospital length of stay (2.2 vs. 4.2 days) in the accelerated discharge group. Importantly, the accelerated pathway was safe and did not show an increase in complications or re-admission rates when compared to the traditional discharge pathway. Other benefits of the accelerated pathway cited by the authors include faster return to work by parents, lower healthcare cost, and a faster return to a daily home routine. Sanders et al⁷ also demonstrated a statistically significant decrease in LOS with an accelerated rehabilitation pathway (3.7 vs 5.0 days). This pathway was also safe and reduced hospital costs by 22%.⁷ The authors have found that most adolescent patients can be discharged within 3 or 4 days with an aggressive rehabilitation approach.

Postoperative Considerations

The postoperative rehabilitation of patients undergoing PSF for AIS builds on the inpatient gains by returning to baseline activity at home and improving strength and confidence. This occurs in parallel with evaluations to ensure adequate healing of the surgical site and arthrodesis of the spine.

After PSF, Tarrant et al⁹ found a median time to return to school of 10 weeks and 77% of patients had returned to school by 16 weeks postoperatively. Another study by these authors¹¹ found that patients with preoperative curves greater than 70 degrees were delayed by approximately 1 additional month in their return to school.

Clearance to return to sporting activity will vary by attending surgeon. A survey of scoliosis surgeons¹⁰ found that 43% of surgeons recommended low-impact, non-contact sports at 6 months after surgery. Additionally, 60% of surgeons permitted contact sports (i.e., soccer, basketball) after 12 months. However, 60% did not recommend participation in higher impact collision style sports (i.e., football, hockey) after PSF.

Most patients can expect to be restricted in their activities until about 3 to 6 months postoperatively. Additionally, it is our practice to wait for resolution of pain and to ensure maintenance correction and progression towards arthrodesis before return to non-contact physical activity. Fabricant et al⁸ retrospectively analyzed a cohort of 42 patients undergoing PSF for AIS. In this cohort with a mean age of 15.0±1.7 years, the average preoperative curve magnitude was 57.67 ±9.38 degrees and the average time to return to athletic activity was 7.4±3.4 months. Moreover, 25 (59%) of patients returned to physical activity at the same level or better than before surgery, but 7 had to change their activity. Those who did not return to sports or did so at lower level most

commonly cited a loss of flexibility and back pain as their reasons. Additionally, these patients were more likely to have a higher preoperative Lenke classification and a lower level of fusion at the time of surgery. For example, while 73% of patients with a T12 distal fusion level returned to their prior activities after surgery, only 20% of patients with an L4 fusion level achieved this outcome. What is reassuring is that no complications related to return to play were reported. Taken together, these data suggest that a return to athletics is a safe and realistic rehabilitation goal following PSF. However, some patients may ultimately change their sport or activity level, depending on the complexity of their deformity.

As a result of surgical intervention around the paraspinal musculature and the fusion that is ultimately achieved in the spine, AIS patients may experience changes in range of motion (ROM) and the muscular function of their spine. These patients will go on to make adaptive changes while performing certain activities.²⁰ This may include increased reliance on leg muscles²⁰ to compensate for weakened paraspinal musculature with forward bends. Physical therapy in the postoperative period should address the loss of flexibility seen as a result of fusion. Additionally, athletes returning to sports will benefit from specific exercises to improve balance, agility and gait while retraining with sports-specific activities.^{22, 21} After the initial healing period, it is the authors' protocol to institute formal physical therapy for sport-specific rehabilitation for patients wishing early return to sports.

CONCLUSION

Adolescent Idiopathic Scoliosis is an entity commonly encountered by pediatric musculoskeletal providers. As outlined above, rehabilitation plays an important role at all stages of the continuum of care of patients with AIS. Preoperative exercise therapies may confer a lasting, albeit modest, benefit to patients not yet indicated for surgery. Coordinated, inpatient postoperative care pathways are proving to be cost-effective, safe, and effective in accelerating the postoperative rehabilitation of patients undergoing PSF for AIS. Lastly, ongoing postoperative rehab will ensure a return to an active lifestyle and, in many patients, a return to a high level of activity.

References

1. Miller NH. Cause and natural history of adolescent idiopathic scoliosis. *Orthop Clin North Am.* 1999;30:343–52.
2. Sui WY, Ye F, Yang JL. Efficacy of tranexamic acid in reducing allogeneic blood products in adolescent idiopathic scoliosis surgery. *BMC Musculoskelet Disord.* 2016 Apr 27;17:187.
3. Wang M, Zheng XF, Jiang LS. Efficacy and Safety of Antifibrinolytic Agents in Reducing Perioperative Blood Loss and Transfusion Requirements in Scoliosis Surgery: A Systematic Review and Meta-Analysis. *PLoS One.* 2015 Sep 18;10(9):e0137886.
4. Bowen RE, Gardner S, Scaduto AA, Eagan M, Beckstead J. Efficacy of intraoperative cell salvage systems in pediatric idiopathic scoliosis patients undergoing posterior spinal fusion with segmental spinal instrumentation. *Spine (Phila Pa 1976).* 2010 Jan 15;35(2):246-51.
5. Oliveira JAA, Filho FAM, Fernandes FV, Almeida PC, de Oliveira VF, Lima Verde SR. Is cell salvage cost-effective in posterior arthrodesis for adolescent idiopathic scoliosis in the public health system? *J Spine Surg.* 2017 Mar;3(1):2-8.
6. Fletcher ND, Andras LM, Lazarus DE, Owen RJ, Geddes BJ, Cao J, Skaggs DL, Oswald TS, Bruce RW Jr. Use of a Novel Pathway for Early Discharge Was Associated With a 48% Shorter Length of Stay After Posterior Spinal Fusion for Adolescent Idiopathic Scoliosis. *J Pediatr Orthop.* 2017 Mar;37(2):92-97.
7. Sanders AE, Andras LM, Sousa T, Kissinger C, Cucchiario G, Skaggs DL. Accelerated Discharge Protocol for Posterior Spinal Fusion Patients With Adolescent Idiopathic Scoliosis Decreases Hospital Postoperative Charges 22. *Spine (Phila Pa 1976).* 2017 Jan 15;42(2):92-97.
8. Fabricant PD, Admoni S, Green DW, Ipp LS, Widmann RF. Return to athletic activity after posterior spinal fusion for adolescent idiopathic scoliosis: analysis of independent predictors. *J Pediatr Orthop.* 2012 Apr-May;32(3):259-65.
9. Tarrant RC, O'Loughlin PF, Lynch S, Queally JM, Sheeran P, Moore DP, Kiely PJ. Timing and predictors of return to short-term functional activity in adolescent idiopathic scoliosis after posterior spinal fusion: a prospective study. *Spine (Phila Pa 1976).* 2014 Aug 15;39(18):1471-8.
10. Rubery PT, Bradford DS. Athletic activity after spine surgery in children and adolescents: results of a survey. *Spine (Phila Pa 1976).* 2002 Feb 15;27(4):423-7.
11. Tarrant RC, Queally JM, O'Loughlin PF, Sheeran P, Moore DP, Kiely PJ. Preoperative curves of greater magnitude (>70°) in adolescent idiopathic scoliosis are associated with increased surgical complexity, higher cost of surgical treatment and a delayed return to function. *Ir J Med Sci.* 2016 May;185(2):463-71.
12. Sanders JO, Haynes R, Lighter D, Niederpruem M, Hollenback C, Johnson L, Nomura S, Arndt D, Bush P, Santiago J, King R, Trottier T. Variation in care among spinal deformity surgeons: results of a survey of the Shriners hospitals for children. *Spine (Phila Pa 1976).* 2007 Jun 1;32(13):1444-9.
13. Watanabe K, Michikawa T, et al. Physical Activities and Lifestyle Factors Related to Adolescent Idiopathic Scoliosis. *The Journal of Bone and Joint Surgery.* 99(4):284–294, Feb 2017.
14. Lonstein JE. Scoliosis: surgical versus nonsurgical treatment. *Clin Orthop Relat Res.* 2006;443:248–259.
15. Mooney V, Gulick J, Pozos R. A preliminary report on the effect of measured strength training in adolescent idiopathic scoliosis. *J Spinal Disord.* 2000;13:102–10.
16. Ko KJ, Kang SJ. Effects of 12-week core stabilization exercise on the Cobb angle and lumbar muscle strength of adolescents with idiopathic scoliosis. *J Exerc Rehabil.* 2017 Apr 30;13(2):244-249.
17. Gür G, Ayhan C, Yakut Y. The effectiveness of core stabilization exercise in adolescent idiopathic scoliosis: A randomized controlled trial. *Prosthet Orthot Int.* 2017 Jun;41(3):303-310.
18. SOSORT guideline committee, Weiss HR, Negrini S, Rigo M, Kotwicki T, Hawes MC, Grivas TB, Maruyama T, Landauer F. Indications for conservative management of scoliosis (guidelines). *Scoliosis.* 2006 May 8;1:5. doi: 10.1186/1748-7161-1-5.

19. Shah Nawaz A, Alghadir A, Abu S, Dilshad A. Effects of Exercise on Spinal Deformities and Quality of Life in Patients with Adolescent Idiopathic Scoliosis. *Biomed Res Int.* 2015;2015:123848.
20. Wang TY, Pao JL, Yang RS, Jang JS, Hsu WL. The adaptive changes in muscle coordination following lumbar spinal fusion. *Hum Mov Sci.* 2015 Apr;40:284-97. Epub 2015 Jan 24.
21. Kakar RS, Simpson KJ, Das BM, Brown CN. Review of Physical Activity Benefits and Potential Considerations for Individuals with Surgical Fusion of Spine for Scoliosis. *Int J Exerc Sci.* 2017 Mar 1;10(2):166-177. eCollection 2017.
22. Pescatello LS, Arena R, Riebe D, Thompson PD. *ACSM's Guidelines for Exercise Testing and Prescription.* Ninth Edition. Philadelphia: Wolters Kluwer/Lippincott Williams & Wilkins; 2014.
23. Kuru T, Yeldan İ, Dereli EE, Özdiñçler AR, Dikici F, Çolak İ. The efficacy of three-dimensional Schroth exercises in adolescent idiopathic scoliosis: a randomised controlled clinical trial. *Clin Rehabil.* 2016 Feb;30(2):181-90.
24. Monticone M, Ambrosini E, Cazzaniga D, Rocca B, Ferrante S. Active self-correction and task-oriented exercises reduce spinal deformity and improve quality of life in subjects with mild adolescent idiopathic scoliosis. Results of a randomised controlled trial. *Eur Spine J.* 2014 Jun;23(6):1204-14.

Authors

Jose M. Ramirez, MD; Department of Orthopaedic Surgery, Alpert Medical School, Brown University, Providence, RI.

Craig P. Ebersson, MD; Department of Orthopaedic Surgery, Alpert Medical School, Brown University; Hasbro Children's Hospital, University Orthopedics, Providence, RI.

Correspondence

Jose_Ramirez@Brown.edu

Craig_Ebersson@Brown.edu

Pediatric Anterior Cruciate Ligament Rehabilitation: A Review

STEVEN F. DEFRODA, MD, MEng; KATHRYN HILLER, BS; ARISTIDES I. CRUZ, Jr., MD, MBA

ABSTRACT

Rehabilitation is crucial in the treatment of ACL injuries, particularly in the pediatric population. Children are often eager to return to their pre-injury level of athletic participation, which may place them at risk for re-injury if rehabilitation protocols are not adequately followed. Contemporary protocols incorporate functional benchmarks rather than solely time-based milestones to better evaluate if patients have adequate strength and function to return to sport activities. Optimization of rehabilitation can lead to safer return to play and minimize the risk of re-injury. Ultimately, successful rehabilitation requires effective communication between the entire care team, including the patient, family, therapist, coaches, trainers, and orthopaedic surgeon in order to optimize recovery from injury.

INTRODUCTION

Increased organized sport participation in children and adolescents has led to an increase in the number of acute and chronic injuries in youth athletes.¹ Among high school athletes, up to 50% of injuries that require surgery involve the knee and 25% of those knee injuries involve the ACL.^{2,3} Beck et al. reviewed the incidence of ACL injury in patients aged 6–18 from 1994–2013 and found an average rate of 121 injuries per 100,000 person-years.⁴ The highest rates were in 17-year-old males (422 per 100,000) and 16-year-old females (392 per 100,000). An important finding was that over the 20-year period, there was 2.3% average annual increase in the rate of injury.⁴ As the rate of injury has increased, so has the number of ACL reconstruction (ACL-R) surgeries in pediatric patients over the last 20 years.⁵ Dodwell et al. examined a state-based database and found that from 1990 to 2009 the rate of pediatric ACL-R increased from 17.6 to 50.9 per 100,000.⁵

Many controversies exist regarding the treatment of ACL injuries in the pediatric population, as they are skeletally immature individuals. Reconstruction of the ACL in a manner similar to skeletally mature patients would require disruption of the physis,⁶ which could result in growth disturbances.⁷ While there have been favorable outcomes regarding initial nonsurgical treatment and delayed reconstruction (until skeletal maturity), these options have

resulted in increased knee instability and a higher risk of osteoarthritis later in life.^{8–10} Various surgical techniques have been developed in order to provide long-term knee stability in pediatric patients, including physeal sparing as well as partial and complete transphyseal techniques.^{11–15} The specific type of procedure to be performed depends on a number of factors, including patient age, activity level, and surgeon preference.

While recent efforts have focused on understanding optimal ACL injury management in the pediatric population, less time has been spent on determining the proper rehabilitation processes that should follow. Adult studies have proven that both post-operative and pre-operative rehabilitation lead to improved functional outcomes.¹⁶ Specific rehabilitation protocols can impact the speed and safety with which patients return to sporting activities.¹⁷ Rehabilitation protocols may vary based on the type of surgery performed; however, both pre- and post-operative rehabilitation are crucial components in managing pediatric ACL injury.¹⁸ The purpose of this paper is to review current trends in pediatric ACL rehabilitation, as well as to identify future areas of study.

NON-OPERATIVE TREATMENT

Nonsurgical treatment has been the traditional approach to ACL injury management in the pediatric population due to the concern of disrupting the physis through surgical reconstruction. Non-operative treatment typically consists of activity modification, physical therapy, and specialized bracing.^{19,20} Moksnes, Engebretsen, and Risberg²¹ outline a four-phase nonsurgical treatment program that emphasizes range of motion, neuromuscular training, and strengthening. In Phases 1 and 2, patients work closely with physical therapists and are provided with exercises to perform at home; they proceed to the next phase only after meeting specific functional milestones. Phase 3 incorporates jumping and landing, open- and closed-chain strengthening exercises, and plyometric drills. Phase 4 consists of a secondary injury prevention program that focuses on functional stability. If recurrent instability occurs despite activity modification and progressing through the treatment program, surgical reconstruction is recommended.²⁰

While nonsurgical treatment preserves the growth plate, many studies have demonstrated its shortcomings, including

an increased risk of instability, meniscal injuries, and chondral injuries.^{8-10,20,22,23} When treated non-operatively, 19.5% of pediatric patients sustained new meniscal injuries after their initial ACL tear, and cartilage injuries had a prevalence of 7.1% two to three years after the initial ACL tear.²² Surgery should be recommended if nonsurgical treatment does not provide sufficient functional stability, if patients continue to have episodes of giving way, if a satisfactory activity level is not achieved, or if there is a significant concomitant meniscal injury.²⁰⁻²² While some surgeons advocate for delayed reconstruction once the physis matures, others have found that if surgery is delayed by ≥ 12 weeks, there is a significantly increased chance of irreparable meniscus injury and lateral compartment chondral injury.²⁴ Furthermore, the severity of the injuries increase with time.²⁵ A recent systematic review of the literature concluded that early ACL-R leads to less meniscal and chondral damage compared to non-operative or delayed surgical treatment.²³ There are currently no high-level studies that directly compare the efficacy of nonsurgical treatment to surgical reconstruction of the ACL in the pediatric population.²⁶

"PRE-HABILITATION"

In the adult population, pre-operative rehabilitation has been shown to improve knee-related functioning, muscle strength, and return-to-sport rates after ACL-R.^{16,27} There is little documentation, however, of the effects of pre-habilitation protocols in the pediatric population. In a case study, Greenberg et al. described a brief pre-operative physical therapy regimen before an all-epiphyseal ACL-R, with gait training, assessment of the patient's maturity level, and ability to follow post-operative instructions.²⁸ The functional goals included no effusion, at least 80% quadriceps strength in the affected leg when compared with the unaffected leg, full extension, at least 120 degrees of active knee flexion, and independence with weight-bearing restrictions. Fabricant et al. recommend activity modification and closed chain rehabilitation following ACL tears in the pediatric population, but no specific recommendations were provided.²⁹

POST-OPERATIVE WEIGHT-BEARING

Generally, surgeons encourage early post-operative weight-bearing following ACL-R, but in the pediatric population, a more restricted weight-bearing protocol may preserve the graft tissue and the physis.²⁸ Some surgeons recommend restricting patients to toe-touch weight-bearing (TTWB) for at least the first week following an all-epiphyseal reconstruction.^{28,30} Weight-bearing as tolerated (WBAT) is advised during weeks 2-4 post-ACL-R until the patient has a normalized gait pattern,³⁰ and full weight-bearing is recommended by post-operative week five.²⁸ Similarly, according to the Hospital for Special Surgery (HSS) protocol, patients

should aim to normalize gait patterns while WBAT during post-operative weeks 4-8.²⁹ In the presence of a concomitant meniscus repair, surgeons generally limit weight-bearing to allow time for the meniscus to heal.^{21,30,31}

RANGE OF MOTION

One of the major goals of post-operative rehabilitation is for the patient to obtain full range of motion (ROM) of the knee. Passive and active exercises are suggested in the early post-operative phase to help improve extension and flexion, including a continuous passive motion machine,²⁸ wall slides, prone dangling, resting extension with a heel prop, and stationary cycling.³⁰ Surgeons tend to rely on time-based criteria when restricting knee motion during the rehabilitation protocol.³² Some surgeons recommend locking the post-operative brace in full extension immediately following surgery for up to three²⁸ or four³⁰ weeks, while both ambulating and sleeping. There is wide variability in the literature regarding post-operative ROM goals. One article recommends reaching 50 degrees of knee flexion by post-operative week four and 90 flexion by week five,²⁸ while another suggests 90 flexion by week two and 120 flexion by week four.³⁰ Others have recommended 90 flexion by week four, 125 flexion by week eight, and full ROM by week sixteen.²⁹ Only Akinleye et al.³⁰ provide specific functional criteria that must be met before unlocking the brace and removing restrictions. Makhni et al. found a wide range of variability in adult ACL-R protocols at academic institutions, similar to the pediatric literature.³³ There is variability in post-operative protocols, but the main goals should be to restore strength and motion as much as possible and to achieve a successful return to play.

STRENGTHENING

Quadriceps activation and strengthening are important goals early in the rehabilitation phase and can be attained through muscle contractions and straight leg raises.²⁸⁻³⁰ Current rehabilitation protocols advocate for progressive strengthening exercises^{29,30} along with neuromuscular training to improve strength, proprioception, balance, and muscle endurance.³⁰ Home exercise programs will help regain strength in the quadriceps, hamstrings, and hip muscles,²⁸⁻³⁰ but it is important to consider the patients' age, maturity level, and parental involvement. Isokinetic testing during postoperative weeks 16 and 24 can help guide the rehabilitation program; if the peak torque deficit is less than 25% of the unaffected leg, more advanced and sport-specific training (including double leg hopping, jogging, agility drills, and double leg plyometric drills) may be initiated.³⁰ According to the HSS protocol, the patient maximizes leg strength during weeks 16 through 20 while the HSS injury prevention program is implemented.²⁹ One study has found that over 50% of

Figure 1. Early (A–C), and late (D–E) ACL rehabilitation exercises.

A. Quad sets, towel is placed under injured leg and patient contracts and relaxes their quadriceps muscle.

B. Straight leg raises. **C.** Quadriceps extensions. **D.** Step ups. **E.** Squats. **F.** One leg squat.



pediatric patients reach 85% of quadriceps strength between two and six months post-ACLR.³⁴ Another study, however, concluded that it takes longer for the pediatric population to regain quadriceps strength than the adult population; after 15 months, only 25% achieved a limb symmetry index (LSI) of greater than 90% on all strength and functional tests.³⁵ These results indicate the need for further research to determine the proper strength exercises and duration of rehabilitation for the pediatric population.

FUNCTIONAL TRAINING

The goal of rehabilitation in post-operative ACL-R patients is to achieve a functional and stable knee.²¹ Many authors advocate functional exercises throughout the rehabilitation

process for this purpose, including specific exercises that target neuromuscular control and muscle strength.^{21,28–30} In the Children’s Hospital of Philadelphia (CHOP) rehabilitation protocol, early functional exercises (weeks 4–16) include proprioceptive neuromuscular facilitation, progressive resistive exercises, leg presses, balance training, squats, single-leg squats, and step-ups. Progression to running, double-leg hop, plyometrics, and sport-specific activities is initiated only after certain functional milestones are met (Figure 1).^{20,28,30} Similarly, the functional goals of the HSS protocol are to demonstrate an athletic-ready stance by week 20 and to feel confident with sport-specific movements by week 28.²⁹ An injury prevention program of neuromuscular training may help to maintain functional stability of the knee with both post-operative and non-operative management.²¹

RETURN TO SPORT

The ultimate goal of the surgical and/or rehabilitation process is to return the patient to the same type, intensity, and frequency of sport as before the injury occurred.^{36,37} Returning to play too early places the patient at a greater risk of re-injury,³⁸ particularly in pediatric and adolescent patients.³⁹ Previously, subjective self-report measures and time-based criteria were used to assess sport readiness in both the adult and pediatric population.^{35,40,41} Objective, functional testing throughout the rehabilitation process will help determine sport readiness at each stage.²¹ Functional testing will reveal strength deficits through the presence of abnormal movement patterns, and it should be considered along with factors such as quadriceps strength, range of motion, and dynamic balance.^{34,35}

Research on return to sport in the adult population has seen a paradigm shift moving away from time-based criteria towards more function-based criteria in order to individualize progress and plan the safest time to return to sport.⁴⁰ Joreitz et al³⁶ have created a protocol for adults comprised of functional goals, guidelines, and recommendations for returning to sport that is currently being studied. No criterion-based measures have been adequately studied, especially in the pediatric population.³⁶ Both the HSS and the CHOP protocols use a combination of time and functional criteria for return to sport. The HSS protocol allows return to sport after 28 weeks and achievement of at least 85% functional single leg hop test compared with the unaffected limb as well as dynamic control and lack of apprehension with sport-specific movements.²⁹ The CHOP protocol, on the other hand, requires that the patient must meet certain functional criteria and be nine months post-operation in order to return to sport.^{28,30} There is a need for further research on the most effective criteria to ensure the safest and most efficient return to sport for the pediatric population.

CONCLUSION

Rehabilitation is crucial in the treatment of ACL injuries, particularly in the pediatric population. Children are often eager to return to their pre-injury level of athletic participation, which may place them at risk for re-injury if rehabilitation protocols are not adequately followed. Newer protocols incorporate functional benchmarks rather than time milestones to evaluate if patients have adequate strength and function to return to sport. Ultimately, the physician and therapist in conjunction with patients, parents, coaches, and trainers should clearly outline the goals and specific phases of ACL-R rehabilitation to align expectations, optimize outcomes, and increase the rates of successful return to sport.

References

- Adirim TA, Cheng TL. Overview of injuries in the young athlete. *Sport Med.* 2003;33(1):75-81. doi:10.2165/00007256-200333010-00006.
- Rechel JA, Collins CL, Comstock RD. Epidemiology of Injuries Requiring Surgery Among High School Athletes in the United States, 2005 to 2010. *J Trauma Inj Infect Crit Care.* 2011;71(4):982-989. doi:10.1097/TA.0b013e318230e716.
- Swenson DM, Collins CL, Best TM, Flanigan DC, Fields SK, Comstock RD. Epidemiology of knee injuries among U.S. high school athletes, 2005/2006-2010/2011. *Med Sci Sports Exerc.* 2013;45(3):462-469. doi:10.1249/MSS.0b013e318277acca.
- Beck NA, Lawrence JTR, Nordin JD, DeFor TA, Tompkins M. ACL Tears in School-Aged Children and Adolescents Over 20 Years. *Pediatrics.* 2017;139(3):e20161877. doi:10.1542/peds.2016-1877.
- Dodwell ER, LaMont LE, Green DW, Pan TJ, Marx RG, Lyman S. 20 Years of Pediatric Anterior Cruciate Ligament Reconstruction in New York State. *Am J Sports Med.* 2014;42(3):675-680. doi:10.1177/0363546513518412.
- Cruz AI, Lakomkin N, Fabricant PD, Lawrence JTR. Transphyseal ACL Reconstruction in Skeletally Immature Patients: Does Independent Femoral Tunnel Drilling Place the Physis at Greater Risk Compared With Transtibial Drilling? *Orthop J Sport Med.* 2016;4(6):2325967116650432. doi:10.1177/2325967116650432.
- Chudik S, Beasley L, Potter H, Wickiewicz T, Warren R, Rodeo S. The Influence of Femoral Technique for Graft Placement on Anterior Cruciate Ligament Reconstruction Using a Skeletally Immature Canine Model with a Rapidly Growing Physis. *Arthrosc - J Arthrosc Relat Surg.* 2007;23(12):1309-1319.e1. doi:10.1016/j.arthro.2007.07.006.
- Aichroth PM, Patel DV, Zorrilla P. The natural history and treatment of rupture of the anterior cruciate ligament in children and adolescents. *J Bone Jt Surg.* 2002;84(1):38-41. doi:10.1302/0301-620X.84B1.11773.
- Schachter AK, Rokito AS. ACL injuries in the skeletally immature patient. *Orthopedics.* 2007;30(5):362-365. <http://www.ncbi.nlm.nih.gov/pubmed/17539208>. Accessed May 27, 2017.
- Wojtys EM, Brower AM. Anterior cruciate ligament injuries in the prepubescent and adolescent athlete: Clinical and research considerations. *J Athl Train.* 2010;45(5):509-512. doi:10.4085/1062-6050-45.5.509.
- Anderson CN, Anderson AF. Pediatric ACL: Evaluation and management. *Curr Orthop Pr.* 2014;25(4):312-320. doi:10.1097/bco.0000000000000134.
- Kocher MS. Physeal Sparing Reconstruction of the Anterior Cruciate Ligament in Skeletally Immature Prepubescent Children and Adolescents. *J Bone Jt Surg.* 2005;87(11):2371. doi:10.2106/JBJS.D.02802.
- McConkey MO, Bonasia DE, Amendola A. Pediatric anterior cruciate ligament reconstruction. *Curr Rev Musculoskelet Med.* 2011;4(2):37-44. doi:10.1007/s12178-011-9076-9.
- Cruz AI, Fabricant PD, McGraw M, Rozell JC, Ganley TJ, Wells L. All-Epiphyseal ACL Reconstruction in Children: Review of Safety and Early Complications. *J Pediatr Orthop.* 2017;37(3):204-209. doi:10.1097/BPO.0000000000000606.
- Lawrence JTR, Bowers AL, Belding J, Cody SR, Ganley TJ. All-epiphyseal anterior cruciate ligament reconstruction in skeletally immature patients. *Clin Orthop Relat Res.* 2010;468(7):1971-1977. doi:10.1007/s11999-010-1255-2.
- Failla MJ, Logerstedt DS, Grindem H, et al. Does Extended Preoperative Rehabilitation Influence Outcomes 2 Years After ACL Reconstruction?: A Comparative Effectiveness Study Between the MOON and Delaware-Oslo ACL Cohorts. *Am J Sports Med.* 2016;44(10):2608-2614. doi:10.1177/0363546516652594.
- van Grinsven S, van Cingel REH, Holla CJM, van Loon CJM. Evidence-based rehabilitation following anterior cruciate ligament reconstruction. *Knee Surgery, Sport Traumatol Arthrosc.* 2010;18(8):1128-1144. doi:10.1007/s00167-009-1027-2.

18. Yellin JL, Fabricant PD, Gornitzky A, et al. Rehabilitation Following Anterior Cruciate Ligament Tears in Children: A Systematic Review. *JBJS Rev.* 2016;4(1):e4. doi:10.2106/JBJS.RVW.O.00001.
19. Ludwig M, Atanda A. Management of anterior cruciate ligament tears in skeletally immature athletes. *Phys Sportsmed.* 2015;43(4):440-447. doi:10.1080/00913847.2015.1084213.
20. Moksnes H, Engebretsen L, Eitzen I, Risberg MA. Functional outcomes following a non-operative treatment algorithm for anterior cruciate ligament injuries in skeletally immature children 12 years and younger: A prospective cohort with 2 years follow-up. *Br J Sports Med.* 2013;47(8):488-494. doi:10.1136/bjsports-2012-092066.
21. Moksnes H, Engebretsen L, Risberg MA. Management of Anterior Cruciate Ligament Injuries in Skeletally Immature Individuals. *J Orthop Sport Phys Ther.* 2012;42(3):172-183. doi:10.2519/jospt.2012.3608.
22. Moksnes H, Engebretsen L, Risberg MA. Prevalence and Incidence of New Meniscus and Cartilage Injuries after a Non-operative Treatment Algorithm for ACL Tears in Skeletally Immature Children. *Am J Sports Med.* 2013;41(8):1771-1779. doi:10.1177/0363546513491092.
23. Fabricant PD, Lakomkin N, Cruz AI, Spitzer E, Lawrence JTR, Marx RG. Early ACL reconstruction in children leads to less meniscal and articular cartilage damage when compared with conservative or delayed treatment. *J ISAKOS Jt Disord Orthop Sport Med.* 2016. http://jisakos.bmj.com/content/early/2016/01/27/jisakos-2015-000012?utm_source=TrendMD&utm_medium=cpc&utm_campaign=Journal_of_ISAKOS%253A_Joint_Disorders_%2526_Orthopaedic_Sports_Medicine_TrendMD_1. Accessed July 5, 2017.
24. Lawrence JTR, Argawal N, Ganley TJ. Degeneration of the Knee Joint in Skeletally Immature Patients with a Diagnosis of an Anterior Cruciate Ligament Tear. *Am J Sports Med.* 2011;39(12):2582-2587. doi:10.1177/0363546511420818.
25. Newman JT, Carry PM, Terhune EB, et al. Factors Predictive of Concomitant Injuries among Children and Adolescents Undergoing Anterior Cruciate Ligament Surgery. *Am J Sports Med.* 2015;43(2):282-288. doi:10.1177/0363546514562168.
26. Anderson CN, Anderson AF. Management of the Anterior Cruciate Ligament-Injured Knee in the Skeletally Immature Athlete. *Clin Sports Med.* 2017;36(1):35-52. doi:10.1016/j.csm.2016.08.003.
27. Alshewaiher S, Yeowell G, Fatoye F. The effectiveness of pre-operative exercise physiotherapy rehabilitation on the outcomes of treatment following anterior cruciate ligament injury: a systematic review. *Clin Rehabil.* 2017;31(1):34-44. doi:10.1177/0269215516628617.
28. Greenberg EM, Albaugh J, Ganley TJ, Lawrence JTR. Rehabilitation considerations for all epiphyseal ACL reconstruction. *Int J Sports Phys Ther.* 2012;7(2):185-196. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3325638/pdf/ijsp-07-185.pdf>. Accessed May 21, 2017.
29. Fabricant PD, Jones KJ, Delos D, et al. Reconstruction of the Anterior Cruciate Ligament in the Skeletally Immature Athlete: A Review of Current Concepts. *J Bone Jt Surgery-American Vol.* 2013;95(5):e28-1-13. doi:10.2106/JBJS.L.00772.
30. Akinleye SD, Sewick A, Wells L. All-epiphyseal ACL reconstruction: a three-year follow-up. *Int J Sport Phys Ther.* 2013;8(3):300-310. <http://www.ncbi.nlm.nih.gov/pubmed/23772346>. Accessed June 8, 2017.
31. Nwachukwu BU, McFeely ED, Nasreddine A, et al. Arthrofibrosis after Anterior Cruciate Ligament Reconstruction in Children and Adolescents. *J Pediatr Orthop.* 2011;31(8):811-817. doi:10.1097/BPO.0b013e31822e0291.
32. Makhni EC, Crump EK, Steinhaus ME, et al. Quality and Variability of Online Available Physical Therapy Protocols From Academic Orthopaedic Surgery Programs for Anterior Cruciate Ligament Reconstruction. *Arthrosc J Arthrosc Relat Surg.* 2016;32(8):1612-1621. doi:10.1016/j.arthro.2016.01.033.
33. Makhni EC, Crump EK, Steinhaus ME, et al. Quality and Variability of Online Available Physical Therapy Protocols From Academic Orthopaedic Surgery Programs for Anterior Cruciate Ligament Reconstruction. *Arthrosc J Arthrosc Relat Surg.* 2016;32(8):1612-1621. doi:10.1016/j.arthro.2016.01.033.
34. Wells L, Dyke JA, Albaugh J, Ganley T. Adolescent anterior cruciate ligament reconstruction: a retrospective analysis of quadriceps strength recovery and return to full activity after surgery. *J Pediatr Orthop.* 2009;29(5):486-489. doi:10.1016/S0162-0908(09)79559-5.
35. Greenberg EM, Greenberg ET, Ganley TJ, Lawrence JTR. Strength and Functional Performance Recovery after Anterior Cruciate Ligament Reconstruction in Preadolescent Athletes. *Sports Health.* 2014;6(4):309-312. doi:10.1177/1941738114537594.
36. Joreitz R, Lynch A, Rabuck S, Lynch B, Davin S, Irrgang J. Patient-specific and surgery-specific factors that affect return to sport after ACL reconstruction. *Int J Sports Phys Ther.* 2016;11(2):264-278. <http://www.ncbi.nlm.nih.gov/pubmed/27104060>. Accessed May 21, 2017.
37. Fabricant PD, Lakomkin N, Cruz AI, Spitzer E, Marx RG. ACL reconstruction in youth athletes results in an improved rate of return to athletic activity when compared with non-operative treatment: a systematic review of the literature. *J ISAKOS Jt Disord Orthop Sport Med.* 2016. http://jisakos.bmj.com/content/early/2016/01/27/jisakos-2015-000013?utm_source=TrendMD&utm_medium=cpc&utm_campaign=Journal_of_ISAKOS%253A_Joint_Disorders_%2526_Orthopaedic_Sports_Medicine_TrendMD_1. Accessed July 5, 2017.
38. Dekker TJ, Rush JK, Schmitz MR. What's New in Pediatric and Adolescent Anterior Cruciate Ligament Injuries? *J Pediatr Orthop.* 2016;0(0):1-8. doi:10.1097/BPO.0000000000000792.
39. Dekker TJ, Godin JA, Dale KM, Garrett WE, Taylor DC, Riboh JC. Return to Sport After Pediatric Anterior Cruciate Ligament Reconstruction and Its Effect on Subsequent Anterior Cruciate Ligament Injury. *J Bone Joint Surg Am.* 2017;99(11):897-904. doi:10.2106/JBJS.16.00758.
40. Keller M, Kurz E, Schmidlein O, Welsch G, Anders C. [Interdisciplinary Assessment Criteria for Rehabilitation after Injuries of the Lower Extremity: A Function-Based Return to Activity Algorithm]. *Sportverletz Sportschaden.* 2016;30(1):38-49. doi:10.1055/s-0042-100966.
41. Barber-Westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. *Arthrosc - J Arthrosc Relat Surg.* 2011;27(12):1697-1705. doi:10.1016/j.arthro.2011.09.009.

Authors

Steven F. DeFroda, MD, MEng, Department of Orthopaedics, Alpert Medical School of Brown University, Providence, RI.
 Kathryn Hiller, BS, Department of Orthopaedics, Alpert Medical School of Brown University, Providence, RI.
 Aristides I. Cruz, Jr., MD, MBA, Department of Orthopaedics, Alpert Medical School of Brown University, Providence, RI.

Correspondence

Steven F. DeFroda, MD
 Department of Orthopaedics
 Alpert Medical School of Brown University
 593 Eddy Street
 Providence, RI 02903
 401-444-4030
 Fax 401-444-6182