# Principles of Ankle-Foot Orthosis Prescription in Ambulatory Bilateral Cerebral Palsy

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**KEYWORDS**

• Cerebral palsy • Ankle-foot orthoses • Gait • AFO prescription

**KEY POINTS**

- Appropriate ankle-foot orthosis (AFO) prescription in ambulatory bilateral cerebral palsy (CP) is driven by the integrity of the plantar flexor–knee extension couple.
- Successful AFO prescription often requires interaction with complementary interventions.
- The angle of the ankle in the AFO must accommodate the knee-extended, midfoot-supported, dorsiflexion range of motion to optimize knee extension and midfoot integrity.
- AFO footwear modifications are necessary to reestablish normal gait function and alignment in AFOs designed to improve walking in CP.

**Video content accompanies this article at http://www.pmr.theclinics.com.**

Ankle foot orthoses (AFOs) are the primary orthoses used to facilitate mobility in cerebral palsy (CP).[1] AFOs encompass the ankle joint and the whole or part of the foot, and are intended to control motion, correct deformity, and/or compensate for weakness.[2] AFOs vary widely by their design, materials, and stiffness. Changing any of these 3 components alters the effect the AFO has on gait.[3,4] For an AFO to improve gait function, it should promote normalization of the alignment of the ground reaction force (GRF) relative to the joints throughout the gait cycle (**Fig. 1**). Bringing the GRF closer to a joint reduces energy expenditure by the lower limb muscles (**Fig. 2**).[5]

For children with CP, alterations of lower extremity strength, tone, selectivity, motor coordination, and associated health conditions all have influence on their ambulatory progress. AFOs are prescribed to minimize the negative impact of these mechanical

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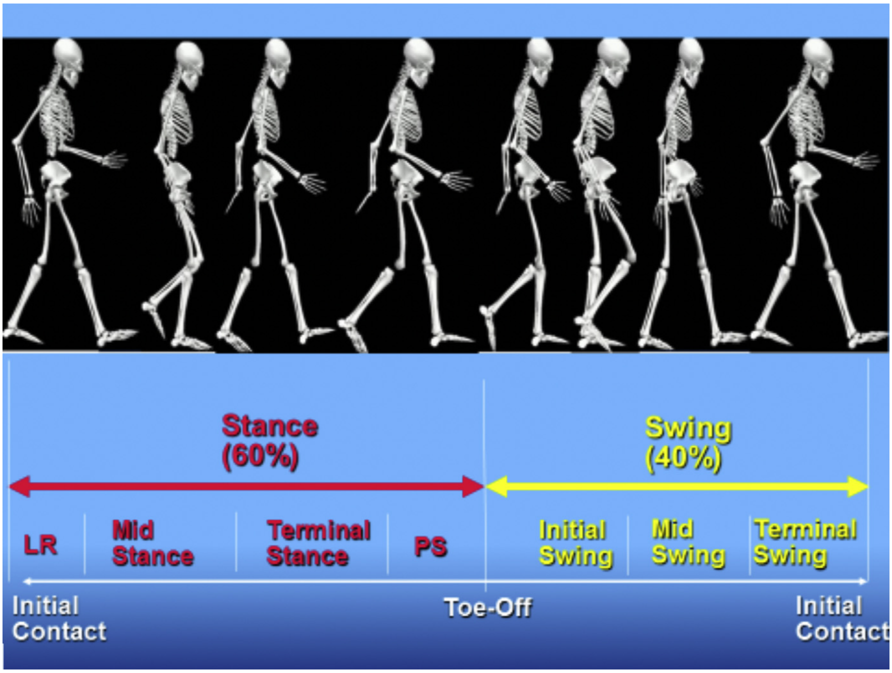


**Fig. 1.** The gait cycle begins and ends with the initial contact of 1 limb and is divided into stance and swing phases. LR, loading response; PS, preswing.

alterations by improving stability for walking, preserving range of motion (ROM), and moderating the deforming forces common to CP. AFOs are likely more effective at preventing, rather than alleviating, contractures and deformity in the foot and ankle.

Challenges exist to the "dosing" of orthoses (duration of wear and design) in ambulatory CP. One concern expressed is that restriction of motion in an orthosis

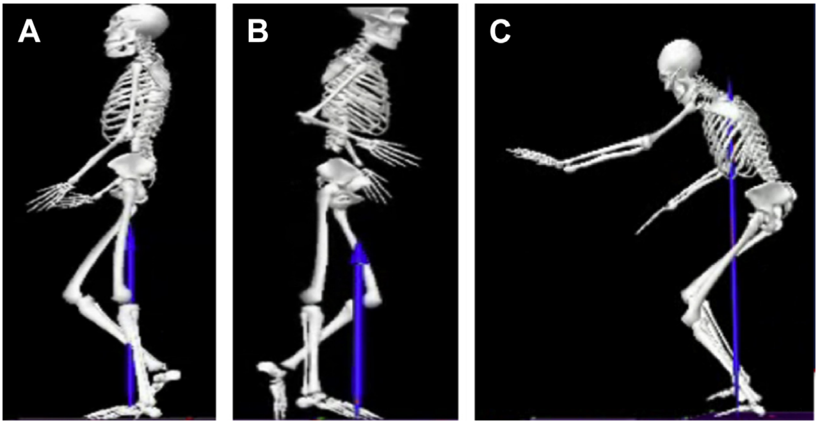


**Fig. 2.** The relationship of body weight to the GRF vector. (*A*) Optimal: GRF through the knee reduces muscle energy requirement. (*B*) GRF in front of the knee (recurvatum) disrupts forward momentum. (*C*) GRF behind the knee (crouch) increases antigravity muscle workload.

may inhibit the emergence of foot and ankle muscle use, limiting the development of typical movement patterns. For children with the mildest central nervous system injury, this concept may have merit. More consistently, impairments of motor control for selectivity and strength in distal musculature are a ceiling for the development of proper muscle function. Goal setting for an AFO, a critical element in prescribing, can create tensions between allowance of motion for functional goals and movement restriction to preserve musculoskeletal integrity. Some functional activities, such as transitioning to standing and stair climbing, benefit from more ankle ROM than is required for walking. Allowing for ankle dorsiflexion, as with a hinged AFO (HAFO), is based on this premise: that ankle motion is essential for the performance of normal movement patterns and postural responses.[6] However, when there is an ankle ROM limitation imposed by a tight gastrocsoleus complex (GSC), the allowance of dorsiflexion creates a circumstance favorable to breakdown of the midfoot. Compromise of midfoot integrity impairs postural response by weakening the foot lever, contributing to an unintended decline of posture in gait (crouch). Therefore, goals must be balanced. Consideration of strength, severity of spasticity, ankle ROM, and anticipation of potential for worsening crouch must factor into the decision rather than assuming that all children will benefit from 1 style of AFO rather than another. Introduction of an articulation also usually compromises intimacy of fit of the brace and control of the hindfoot may be lost. Increased mediolateral motion may increase and skin issues may result.

Research shows that AFOs affect a variety of gait parameters; however, reported outcomes are not all in agreement. There is wide variability in the existing CP/orthotic outcomes research. Inadequacy in the descriptions of participants (tone, Gross Motor Function Classification System [GMFCS], ROM, gait type), AFO details (type, motion, materials, goals), and testing protocols (controls, randomization, acclimation) are cited to account for this.[7]

A recent systematic review of posterior AFOs in ambulatory CP offers an overview of the studied impacts of posterior AFOs (this review had limited data for the use floor reaction AFOs [FR-AFOs]). Pooled data revealed strong evidence for benefit to temporal spatial parameters, stride length more than cadence more than gait speed, and moderate evidence for improvements in gross motor function as measured by relevant subsets of the Gross Motor Function Measure and Pediatric Evaluation of Disability Inventory. There was limited, nonsupportive evidence of impact on balance, activities of daily living, stair climbing, activity level, or energy costs. Improved ankle kinematics for equinus gait in stance and swing were noted, but there was no reported change in knee and hip kinematics. Gait parameters improved in unilateral CP to a greater degree than bilateral CP.[8] Orthoses with trim lines that encompass only the foot, such as the University of California Biomechanics Laboratory (UCBL) and supramalleolar orthoses (SMOs) may have some benefit to bony deformity risks; however, they do not have measurable impact on gait.[9]

## NORMAL MOTION AND FUNCTION OF THE FOOT DURING GAIT

Readers less familiar with hindfoot and midfoot anatomy and motion are referred to https://www.youtube.com/watch?v=0R4zRSE_-40 4:52-5:15 & 5:52-6:57.

Successful AFO management in ambulatory bilateral CP requires a foundational understanding of the typical function of the ankle and foot during the gait cycle. The subtalar joint constitutes the articulation between the talus and calcaneus (**Fig. 3**). It acts synergistically with the midfoot and ankle joints in all 3 planes of motion with

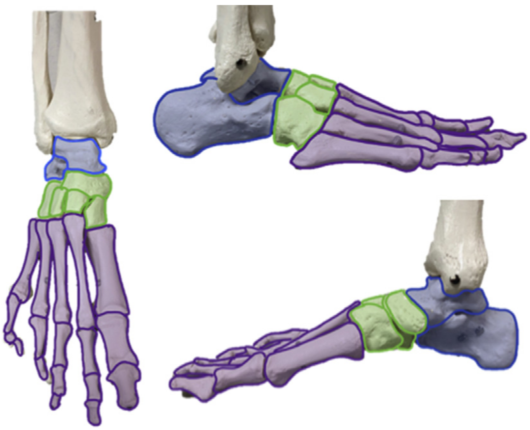

**Fig. 3.** Typical anatomy of the hindfoot (*blue*), midfoot (*green*), and forefoot (*purple*).

an axis nearly 45° out of both the axial and coronal planes (**Fig. 4**A). Subtalar motion is comparable with a miter gear, converting internal and external rotation of leg into pronation and supination of the foot respectively (**Fig. 4**B).

Our limbs cycle through these motions (**Fig. 5**) across the gait cycle. A pronated foot is supple and ideal for both shock absorption and adaptation to variations in terrain needed during weight acceptance (loading response). A supinated foot is rigid, serving as a strong lever arm for the calf musculature to exert the force required to propel the limb forward at push-off. When the foot initially comes into full contact with the floor, the leg internally rotates maximally, and the foot pronates. Pronation occurs primarily through the subtalar joint by eversion of the calcaneus. Calcaneal eversion allows the talus to adduct and plantar flex, which unlocks the midfoot as the talonavicular and calcaneocuboid joints gain a parallel or convergent axis (**Fig. 6**).

As soon as body weight is fully transferred to the outstretched stance limb, it begins to externally rotate as the pelvis and swing limb rotate forward. External rotation of the limb lifts the talus into a dorsiflexed and abducted position, allowing inversion of the calcaneus. The axes of the talonavicular and calcaneocuboid joints become progressively divergent and the flexibility of the foot declines.

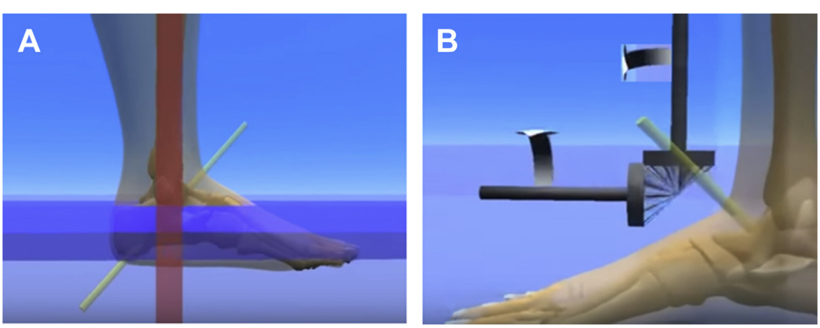


**Fig. 4.** (*A*) Axis of the subtalar joint. (*B*). Relationship of shank rotation and foot motion. (*Courtesy of* [*B*] Dr. Glass DPM; available at https://www.youtube.com/watch?v=0R4zRSE_-40; with permission.)

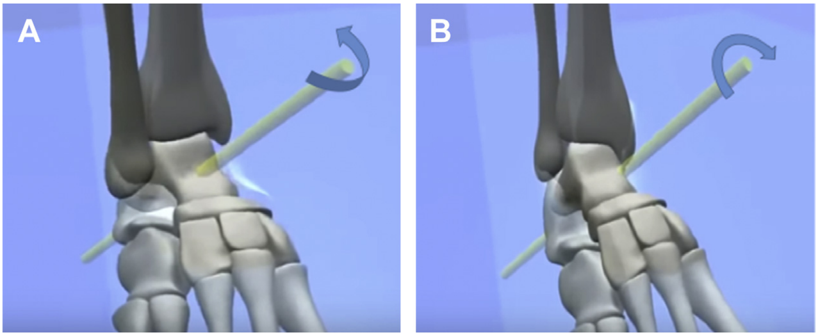


**Fig. 5.** (*A*) Leg internal rotation coupled to foot pronation. (*B*) Leg external rotation coupled to foot supination.

The ability of the foot to become a progressively rigid lever is critical to stability in midstance and torque production by the plantar flexors during terminal stance (Fig. 7).

## THE PLANTAR FLEXOR–KNEE EXTENSION COUPLE

The soleus restrains excessive motion of the tibia (shank) as the ankle dorsiflexes during midstance (second rocker). The impact of the restrained shank on knee stability during the second rocker is known as the plantar flexor–knee extension couple (PF-KE). The effectiveness of the PF-KE in CP depends on 3 elements.

1. Function of the plantar flexors: strength, timing, tone, and length
2. Structural integrity of the bones and ligaments of the foot (lever arm integrity)
3. Direction of foot progression during walking (foot progression angle)

When any of these elements are disrupted, the function of the plantar flexors to act as knee stabilizers is compromised. The child may have to rely on energy-inefficient patterns of muscle activity, such as continuous quadriceps activity in stance, to maintain knee extension (see Fig. 2C).

Children's body mass, proximal tone, contractures, and strength influence the force requirement of the PF-KE and thus its effectiveness. In that sense a stabilizing orthosis

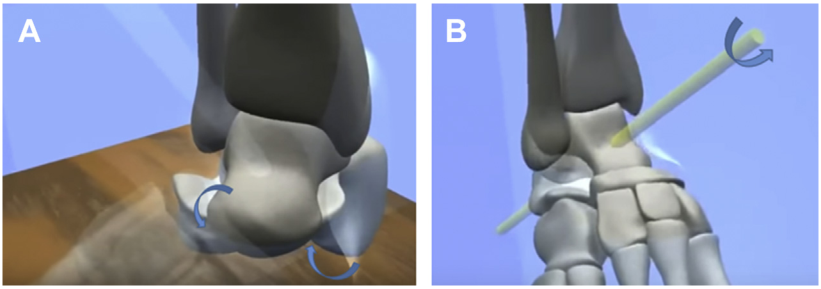


**Fig. 6.** (*A*) Subtalar pronation: talus plantar flexion and adduction with calcaneal eversion. (*B*) Foot pronation: midfoot arch is flattened (unlocked) and the midfoot and forefoot can dorsiflexion and abduct.

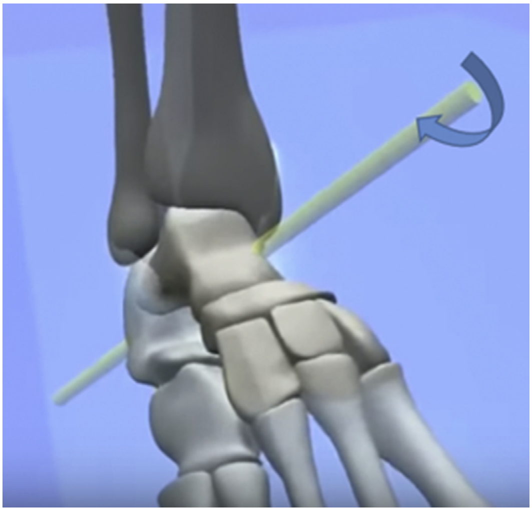

**Fig. 7.** Foot supination: midfoot arch narrows and peaks (locks), restricting midfoot and forefoot motion.

that works from the bottom up may be overwhelmed by top-down impairments. As such, orthopedic referral to improve ankle ROM, restore foot integrity, and address proximal deformities is often necessary for an AFO to provide benefit to more involved children.

## FOOT AND LEG DEFORMITIES AND DEVIATIONS OF THE PLANTAR FLEXOR–KNEE EXTENSION

Children with CP often develop foot deformities that disrupt the normal pattern of subtalar joint motion and the benefits thereof. Three foot and ankle malalignments are common in CP.[9] Equinus and equinoplanovalgus are common in bilateral CP. Equinus is the result of fixed or dynamic GSC shortening, resulting in calcaneal plantar flexion. This condition creates an excessive PF-KE (see **Fig. 2**B). Equinus in bilateral CP commonly gives way to equinoplanovalgus with calcaneal plantar flexion/eversion and associated excessive midfoot pronation. This midfoot compromise results in substantial weakening of the PF-KE (see **Fig. 2**C).

## EQUINOPLANOVALGUS: MIDFOOT BREAKDOWN IN BILATERAL CEREBRAL PALSY

Equinoplanovalgus foot deformity is common, although not universal, in bilateral CP. Equinoplanovalgus is problematic because although calcaneal eversion with pronation of the subtalar joint is normal during loading response, the foot must sufficiently recover to a supinated position to respond to plantar flexor force effectively. Failure to supinate adequately limits the development of the foot rigidity necessary for an effective PF-KE. This inadequacy becomes further amplified during terminal stance when propulsive force generation is required. The propulsive force of the gastrocsoleus on a supple, pronated foot stresses the ligamentous and bony structures of the medial midfoot, which elongate and deform over time.

Several forces favor the persistent foot pronation that eventually progresses to the equinoplanovalgus foot.

- Children with bilateral CP are typically transitioning to weight bearing between 18 and 60 months, when pronation of the foot is physiologic.[10]
- Internal rotation of the lower limb as a result of persistent femoral anteversion.
- A tight GSC acts to both limit ankle dorsiflexion and hold the calcaneus in a plantar flexed and everted position. During second rocker the dorsiflexion becomes a shared motion between the ankle and the foot as GSC tethering of ankle dorsiflexion forces this motion to occur in the midfoot. A so-called second or little ankle develops as the midfoot become excessively dorsiflexed and abducted (equinoplanovalgus) (**Fig. 8**).

This condition is a good example of bony deformities in need of orthopedic evaluation before orthotic intervention. Commonly, as weight bearing progresses and the foot lever fails, the internally rotated femur and abducted forefoot generates a torque on the tibia that promotes external torsion of this bony segment. The combination of heel equinus, talonavicular subluxation, midfoot break, and external tibial torsion contributes to lever arm dysfunction commonly associated with crouch[11] (**Fig. 9**).

## GROWTH AND STAGES IN BILATERAL CEREBRAL PALSY GAIT

Activity levels, tone, strength, deformity, and body mass all affect changes in the gait patterns of children with bilateral CP. Graham and Rodda[12] characterized these gait patterns and offered treatment schemata for each. Although this is not a strict continuum in bilateral CP, it helps clinicians to understand the key components for an orthotic prescription.

Early walking for children with bilateral CP is characterized by a plantar flexed ankle position caused by GSC shortening. Frequently this more dynamic than static and proximal tone is often limited. In these, usually smaller, children there is ample integrity of the foot relative to body mass, so that the PF-KE is strong, promoting knee extension during all phases of stance. This early stage is referred to as toe walking or equinus gait (**Fig. 10**A). When there is more significant proximal muscle tone, shortening, or weakness, as occurs with growth and weight gain, the result is increased hip and knee flexion during stance. In time, the integrity of the foot lever begins to compromise and the PF-KE with it. As the stance limb accepts the full weight of the body, the knees and hips become biased toward flexion. This stage characterizes jump gait, and knee and hip extension are incomplete during stance (**Fig.10**B, C). These 2 gait patterns are common to GMFCS levels I to III.

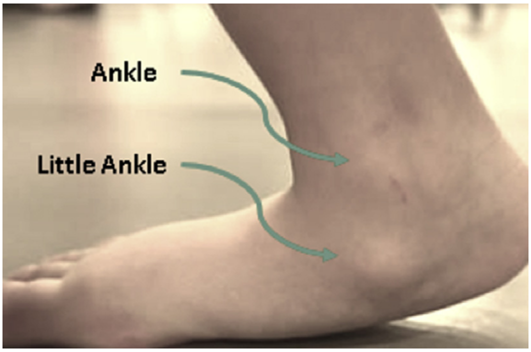


**Fig. 8.** Little ankle. Dorsiflexion occurs through the midfoot joints rather than the true ankle joint.

**Fig. 9.** Talonavicular subluxation, midfoot breakdown, and external tibial torsion contributing to lever arm dysfunction during crouch gait.

With progression of proximal tone and weakness, and lever arm dysfunction at the foot and tibia, the PF-KE couple weakens further and apparent equinus develops (**Fig. 10**D). Toe walking at this stage is reflective of flexion at the knee and hip flexion, rather than true plantar flexion of the ankle and foot. This position can occur as the

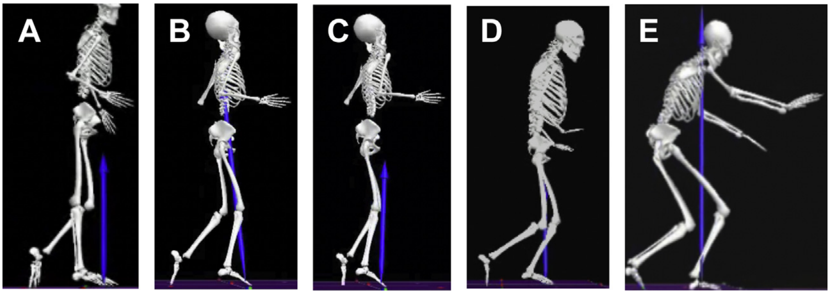


**Fig. 10.** (*A*) Equinus: ankle plantar flexed, knee and hip extended (Video 1). (*B*, *C*) Jump gait: ankle plantar flexed, knee and hip flex then jump back into incomplete extension (Video 2). (*D*) Apparent equinus: toe walking reflects knee and hip flexion (Video 3). (*E*) Crouch: ankle dorsiflexion, knee and hip flexion (Video 4).

natural history in bilateral CP, with a plantar flexed calcaneus and midfoot dorsiflexion but is also frequently seen when GSC release allows calcaneal dorsiflexion. Finally, the fully compromised PF-KE, with foot and ankle dorsiflexion, proximal flexion contractures, and worsening muscle strength to body mass ratio, leads to crouch gait, with severe knee and hip flexion (**Fig. 10**E). This gait pattern is nonsustainable or declining through adulthood. These last 2 gait types commonly function at GMFCS III to IV.

The major goal of orthotic management in bilateral CP is, from the bottom up, to dampen the progressive compromise of the PF-KE couple in stance; the product of proximal tone, relative strength decline, and progressive lever arm dysfunction. This goal may be beyond the capacity of an orthosis to manage and appropriate top-down complementary interventions must be pursued.

## NAMING CONVENTIONS AND BASIC MATERIALS SCIENCE FOR LOWER LIMB ORTHOSES

Orthoses are named by the joints they cross; for example, an AFO is an orthosis that encompasses the ankle and foot. A knee AFO is an orthosis that encompasses the knee, ankle, and foot. This naming convention applies to upper or lower limb orthoses, and spinal orthoses. Orthoses are thought to provide direct control to the joints they encompass and provide indirect control of the next joint proximal. For example, an AFO provides direct control over the ankle and indirect control over the knee. It is possible to increase or decrease the effect an AFO has on knee motion by adjusting the amount of control over the ankle joint. The amount of influence is achieved through the materials selected, the trim lines of the orthosis, and various types of mechanical ankle components (eg, joints, straps) available.

A few of the most common materials used for custom AFOs are copolymer, polypropylene, and polyethylene plastics. Plastics offer the advantages of custom molding, creating an intimate contact with the foot and ankle of the wearer. Some plastics are very flexible, and some are more rigid. These different types of plastics are chosen based on the goals of the orthosis. If the goal of the AFO is to restrict motion or increase support to the leg, a more rigid plastic can be used; if the goal of the AFO is to allow greater joint motion, more flexible plastics can be used. Off-the-shelf carbon fiber products offer a lighter-weight alternative to plastics and may offer some measure of energy storage/return. A carbon fiber AFO can often interface with a custom-molded plastic supramalleolar AFO to achieve more intimate contact.

Orthotic trim lines delineate how much of the limb is encompassed by the plastic material and affect the amount of control or support provided to the user. For example, the trim lines of a typical solid-ankle AFO (SAFO) cross the ankle at the apices of the malleoli, whereas the trim lines of a typical posterior leaf spring AFO cross the ankle posterior to the apices of the malleoli. Because there is less plastic surrounding the ankle to resist motion during ambulation, the posterior leaf spring AFO allows more dorsiflexion ROM during stance than the SAFO. In a similar manner, the amount of support provided can be modified by changing the amount of plastic on the bottom of the foot, or the foot plate. The shorter the foot plate, the less supportive the orthosis. Trim lines can be considered another feature of the AFO that should be customized to suit the needs of each patient.

Similarly, various mechanical ankle components can be used to limit or encourage motion at the ankle. It is helpful to think of these mechanical components in relation to their function. Some joints, such as the Tamarack joint (**Fig. 11**), have viscoelastic properties that provide assistance into dorsiflexion. Other components, such as the dorsiflexion restraint strap, can provide dorsiflexion restraint, or stop it entirely, in smaller patients. The range of lower limb orthotic componentry continues to expand

**Fig. 11.** A HAFO with free dorsiflexion ROM and a plantar flexion stop set at 90°. Optimal use requires true ankle dorsiflexion ROM and an intact PF-KE couple.

with technological advances. More componentry options and advanced technologies are discussed later in this article.

## ORTHOTIC MANAGEMENT OF GAIT DYSFUNCTION IN BILATERAL CEREBRAL PALSY

When the goal of an AFO is to promote ambulation, the appropriate orthotic prescription, regardless of the age or GMFCS level of the child, requires the clinician to perform a thorough physical examination and observational gait analysis. Identifying the gait type is useful in guiding orthotic options. Appropriate strengthening, tone reduction, and orthopedic interventions should be promoted. Lower-limb orthoses function optimally when designed based on sound biomechanical reasoning and when used in conjunction with complementary interventions (Fig. 12).

## EQUINUS GAIT

Children with equinus gait typically present with excessive knee extension (excessive PF-KE couple). Although these children may appear to achieve a flat foot during midstance, physical examination commonly reveals hypertonicity of the plantar flexors and limited ankle dorsiflexion ROM. It should be appreciated that children often achieve this flat foot posture by stealing ROM from the knee joint or the foot, resulting in undesirable compensations of recurvatum at the knee or dorsiflexion of the midfoot. Unless the hypertonicity and limited ankle ROM are addressed or considered within the orthotic design, the orthosis will be ineffective in improving gait function. Therefore, orthotic treatment goals for this gait type depend on the severity of GSC

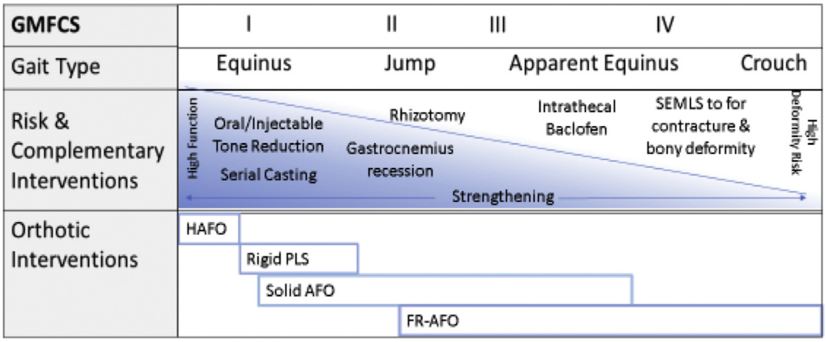


**Fig. 12.** The general relationship between GMFCS level and gait dysfunction in CP. As deformity risk increases and function decreases, interventions are often more involved. PLS, posterior leaf spring; SEMLS, single-event multilevel surgery.

shortening and the effectiveness of complementary interventions in restoring ankle dorsiflexion. If adequate gastrocnemius length is achieved, the orthosis can allow dorsiflexion during stance and activities such as stair climbing and transition from floor to standing.

**Fig. 13.** A custom-molded thermoplastic PLS AFO with posterior reinforcement to increase stiffness as needed. Provides minimal second rocker support, promotes swing clearance while supporting mild foot deformity.

Because calf tone is predominant in equinus gait, management considerations primarily surround the GSC and control of the midfoot. A posterior leaf spring (PLS) AFO (**Fig. 13**) with sufficient stiffness encourages a heel-first initial contact by controlling excessive swing phase plantar flexion and allows ankle dorsiflexion ROM during stance. For younger children with CP, commonly prescribed orthoses for equinus are an articulated or HAFO with a plantar flexion stop at 90° (see **Fig. 11**) or a traditional, very flexible, PLS AFO (see **Fig. 13**). These types of orthoses are not effective when spasticity of the GSC limits true ankle dorsiflexion ROM and should be reserved for children with issues isolated to swing phase. Allowing motion at the ankle when the GSC range is restrained is detrimental to the little ankle (midfoot) and ultimately compromises stance phase stability. As the child grows, consider that, although more flexible AFO designs allow motion at the ankle during this stage of development, this same motion may be detrimental to stance phase stability as spasticity increases and more severe gait deviations develop.

## EQUINUS GAIT WITH RECURVATUM

Children who have been less responsive to efforts at restoring gastrocnemius ROM often present with a degree of equinus associated with recurvatum. AFO design must accommodate this ROM limitation. To ensure the child's dorsiflexion ROM is coming from the ankle and not the midfoot, the ankle evaluation must be done with the knee extended and the midfoot bias toward supination/heel varus because full knee extension ROM is required for normal gait function. If clinicians seek to reestablish normal gait patterns, the give-and-take nature of the ankle and knee joint must be understood. Most children with CP achieve a greater degree of ankle dorsiflexion ROM with the knee flexed, rather than extended, which should be taken into consideration during orthotic design decision making.

Difficulties achieving a successful orthotic intervention for these children are often related to a mismatch of the patient's knee-extended, midfoot-supported, ankle dorsiflexion ROM and the angle of the ankle in the AFO (AA-AFO) (**Fig. 14**). If, on

**Fig. 14.** AA-AFO is the angle of the foot relative to the tibia within the AFO. The AFO on the right shows a plantar flexed AA-AFO with in-the-shoe wedging on the plantar surface to accommodate the contracture present. The AFO on the left shows a plantigrade/90° AA-AFO.

examination, neutral dorsiflexion is not available at the true ankle (ie, knee flexion or midfoot dorsiflexion is substituted for true ankle dorsiflexion) and an AFO is set at 90°, the structural stability of the midfoot is lost and the orthosis can contribute to progressive lever arm dysfunction, discomfort, skin breakdown, and potential abandonment of the orthosis. In addition, because of the interactive nature of ankle and knee joint ROM, it is likely that the AFO will not effectively address gait deviations occurring at the knee. Therefore, it is the knee-extended, midfoot-supported, ankle dorsiflexion ROM that determines the AA-AFO. Understanding the synergistic nature of the midfoot, ankle, and knee joints allows clinicians to identify children whose range limitation is such that surgical intervention is an appropriate consideration before AFO prescription. If a knee-extended ankle plantar flexion contracture greater than 10° exists, AFO accommodations inside the shoe can become a barrier to successful use of the orthosis.

Because of the aforementioned risks of misidentifying ankle dorsiflexion ROM in children with equinus gait who show recurvatum, a PLS or HAFO is likely unsuitable. Gait abnormalities in these children are best managed with an SAFO (**Fig. 15**). SAFOs are designed to prevent ankle dorsiflexion and plantar flexion during stance phase and, in doing so, provide indirect support to, or control of, the knee joint. Because the SAFO encompasses a greater surface area of the lower limb, it is also indicated when there is a need to control undesired triplanar deformity of the midfoot.

When the gastrocnemius does not have sufficient length to allow ankle dorsiflexion during stance, children maintain forward progression of their bodies by stealing

**Fig. 15.** Custom-molded thermoplastic SAFO. Designed to provide triplanar control of foot and ankle deformities and improve control of the knee joint during ambulation. Can be used with or without the inner boot seen here.

motion from the midfoot (breakdown) or knee (recurvatum). This concept still holds true if it is the AFO that is limiting ankle dorsiflexion ROM (rather than a physiologic contracture). Because available passive ankle dorsiflexion ROM is a major contributor to recurvatum during stance phase,[13,14] the AA-AFO must sufficiently accommodate the plantar flexion contracture of the AFO-footwear combination (AFO-FC) to encourage appropriate knee extension (**Fig. 16**). The position of the ankle within the AFO is a key determining factor in the ability of the AFO in controlling recurvatum. In order to accomplish this, the SAFO should accommodate the plantar flexion contracture through use of wedging material. Appropriate shoe wear to place the lower limb in proper alignment adds further control (discussed later). Accommodation of the ankle plantar flexion contracture also improves control of the midfoot within the orthosis, which prevents skin callusing and discomfort during weight bearing. An AFO can be used to limit midfoot breakdown through strong soft tissue support under the subtalar joint, but only if the contracture is first accommodated.

## JUMP GAIT

Jump gait is characterized by ankle plantar flexion in stance with excessive flexion of the knees and hips. The PF-KE is insufficient to fully extend these proximal joints against stiff and weak proximal muscles. Complementary treatments are focused on proximal tone reduction and strengthening. Correction of ankle and foot deformity and stabilization of the ankle in the sagittal plane should be prioritized over allowing ankle motion at this stage. Orthotic management of jump gait must be focused on reestablishing the function of the foot as a rigid lever by accommodating existing gastrocnemius contracture and supporting the midfoot within the AFO. This focus optimizes the ability of the orthosis to support appropriate knee extension during stance. If properly aligned, the AFO can facilitate larger step length, which can encourage normal lengthening of the hip flexors and the GSC, potentially enhancing the therapeutic effects of spasticity management.

For smaller children with mild amounts of knee and hip flexion during ambulation, an SAFO that is stiff enough to support the weight of the body during single-limb support

**Fig. 16.** The effect that proper AFO-FC alignment can have on equinus gait with recurvatum. The AA-AFO must match the child's ankle ROM limitations. The wedging under the AFO in combination with the effective shoe heel height create an alignment favorable to correction of recurvatum.

**Fig. 17.** A custom-molded thermoplastic FR-AFO. Also known as a ground reaction AFO. This AFO more effectively increases knee extension by replacing the proximal anterior strap with a rigid anterior panel.

is most appropriate. As the degree of stance phase knee flexion becomes more severe with increasing body mass, an FR-AFO (or ground reaction AFO) may provide greater support at the knee (**Fig. 17**). The rigid anterior panel helps resist excessive knee flexion by acting synergistically with the rigid toe plate of the FR-AFO. As with any AFO design, accommodation of existing ankle contracture and proper realignment of the lower limb in the coronal and transverse planes is key to management of stance phase deviations at the knee.

## APPARENT EQUINUS

Because of the growing influence of proximal impairments, complementary interventions must be multilevel, often involving systemic tone reduction and orthopedics to effect a more upright posture. The AFO must ensure that midfoot stability is maintained. Allowing midfoot dorsiflexion in order to keep the foot plantigrade is undesirable in this population because it represents a failure of the foot as a rigid lever for the GSC to act on and can be expected to worsen over time. For smaller, higher-functioning children who present with apparent equinus and lesser amounts of hip and knee flexion, an SAFO with appropriate stiffness, alignment, and accompanying footwear effectively increases stance phase knee extension. Commonly, an FR-AFO is necessary to accomplish this.

Either of these AFO designs can function to support the midfoot, improve alignment of the lower limb, and enhance the PF-KE couple as long as the angle of the ankle in the AFO accommodates existing contractures. A plantar flexed angle of the ankle in the AFO in this population mitigates some of the negative effects of a spastic or contracted GSC and improves control of the midfoot by creating less tension on both the midfoot and the knee joint. Relaxing the GSC at the ankle improves the ability of the AFO to increase knee extension, because of the biarticular nature of the gastrocnemius. Slight plantar flexion within the AFO also resists midfoot compromise. A full-length toe plate increases the length of the mechanical lever arm of the orthosis, increasing resistance to knee flexion in stance. The effectiveness of the FR-AFO in improving knee extension depends on successful attention to proximal muscle impairments. FR-AFOs in isolation (without medical or surgical management of the proximal segments) in this population can result in suboptimal management of gait dysfunction.

## CROUCH GAIT

When the PF-KE couple becomes fully compromised, the result is crouch gait. This gait is characterized by excessive foot and ankle dorsiflexion with severe knee and hip flexion and is frequently associated with rotational deformity. This gait pattern presents a major challenge to successful orthotic intervention. Children with crouch gait who present with slow walking velocity, weak plantar flexors, and an externally rotated foot progression angle were found to benefit the most from bilateral FR-AFO intervention.[15] Other investigators have considered greater than 15° of external tibia rotation a contraindication.[16] The primary goal for AFOs for children with crouch gait is to reestablish the PF-KE couple, increase knee extension, improve step length, and improve gait speed. Commonly, multilevel orthopedic interventions are also being considered for this population. Proximal limitations of hip and knee flexion ROM and external foot progression angle related to tibial torsion may need to be addressed to provide maximal benefit.

Selecting the appropriate angle of the ankle in the AFO remains key to successful orthotic management of crouch gait. It is the most predictive factor in determining how much improvement in knee extension can be expected from an AFO used to treat excessive knee flexion.[17] Effectiveness also depends on the stiffness of the orthosis in combination with the shoe and the alignment of the AFO. Although limited, there is evidence that AFOs used after single-event multilevel surgery (SEMLS) provide greater improvements in gait parameters than SEMLS alone,[18] supporting the idea that surgical and orthotic intervention both play important roles in achieving a more upright posture.

## ANKLE FOOT ORTHOSIS TUNING CONCEPTS

Commonly, an AFO is designed in isolation, meaning that little consideration is given to the effect that footwear can have on the overall effectiveness of the orthosis. The notion that footwear must be considered as an integral part of the orthotic prescription for ambulatory children with CP was brought to the mainstream by Elaine Owen[19] MBE, MSc, SRP, MCSP. This approach prioritizes realignment of the shank (or tibia) and the thigh to encourage normal motion of these segments throughout each phase of gait. Foundational to successful AFO intervention is the concept that realignment of the shank into a normal position (10° inclined) is possible, even for children with limited ankle ROM, because the AFO-FC can recreate this normalized position. **Fig. 18** shows a child with an angle of the ankle in the AFO set at 7° plantar flexion with modifications done to the footwear that realign the shank to a position of 10° inclined to vertical.

**Fig. 18.** The beneficial effects of proper AFO-FC tuning. AA-AFO set at 5° plantar flexed to accommodate contractures and maintain good alignment of the midfoot. Heel wedging inside the shoe to accommodate contracture and shoe modifications realign the shank to a normal position. Shoe modifications increase knee extension to create big V. Big V may assist in maintaining normal length of hip flexors and gastrocnemius.

Reestablishing the inclined position of the shank during stance phase mimics the position of the lower limb typically created by normal ankle dorsiflexion ROM and ankle stiffness that many children with CP are lacking. Additional benefits include more normal alignment of the center of mass over the base of the foot and anterior to the knee.

Children who benefit the most from this approach are those lacking ankle dorsiflexion ROM and who therefore require an SAFO. The potential drawbacks to a design that restricts motion at the ankle can be addressed through modifications to the AFO-FC. The SAFO provides necessary stability to the ankle and knee during midstance because of its restriction of ankle dorsiflexion; however, the entrance to midstance (initial contact and loading response) and exit from midstance (terminal stance) must be optimized by modification of the shoe sole. This modification is accomplished by changing the profile of the heel and the forefoot of the shoe (see Fig. 18). Modification of the heel profile can speed up or slow down the rate at which the foot becomes flat on the floor, allowing the clinician to provide more or less stability to the knee during loading response. The forefoot profile determines the exit from midstance, meaning it establishes the amount and timing of knee stability through terminal stance. Modification of the forefoot profile is ideally done with a point-loading rocker. These sole modifications require increased sole height. Sole heights can effectively accommodate ankle PF contractures up to 10° before the sole height limits the utility of this approach. Contractures of greater magnitude likely require surgical consideration.

The amount of shank inclination and the heel and sole profile of the AFO-FC are optimized using video gait analysis and GRF data to go through a process called tuning. Tuning refers to the process of making small adjustments in order to optimize the function of the AFO-FC for a specific activity, most commonly walking. Ideally, prescription of an AFO-FC for children with CP includes a high degree of collaboration between the physician, physical therapist, family, and orthotist. The use of the word tuning is widespread among orthotists in the United States, although only a handful of clinical groups are fully engaging in this process as it was originally intended. Perhaps one of the most important results of Owen's[19] efforts in the United States is the enhanced focus on alignment principles for lower limb orthotics in general. Repositioning of the shank and thigh and consideration of the effect of the footwear on the function of the

AFO have become more common since the introduction of this approach, regardless of the type of AFO used. The changes brought about by exposure to this treatment philosophy have without a doubt improved the standard of care for children with CP.

## MATERIALS AND COMPONENTRY FOR LOWER LIMB ORTHOSES

The amount of support provided by an orthosis is heavily influenced by the materials and componentry available. AFO fabrication has traditionally been completed using various types of heat-moldable plastics, or thermoplastics, as mentioned previously. In general, thermoplastic AFOs allow small changes to be made to accommodate the child's growth. Custom-molded AFOs, which are molded intimately to the children's anatomy, allow small changes to be made as they grow. This intimate fit can be ideal to meet specific treatment goals. Prescribing providers should recognize that off-the-shelf or custom-fit thermoplastic AFOs are fabricated from size charts that are not custom molded, which can compromise the necessary intimacy of fit and loss of control of deformity or support.

Recent advances in the materials and componentry available have increased the orthotic design options significantly. AFOs made of carbon fiber behave differently than AFOs made of other materials because of the properties of the material. Depending on the specific design, carbon fiber AFOs can provide energy storage and return, which means that energy is stored in the AFO as the ankle dorsiflexes during a step, and energy is returned as the AFO is unloaded. This concept is commonly referred to as dynamic response and is thought to mimic the typical function of the ankle muscles during walking more closely than thermoplastics. Carbon fiber AFOs such as the Kiddie Gait from Allard USA, and a multitude of others, provide dynamic response and are appropriate for children with mild strength deficits, mild foot deformities, and who have successful tone management in place. Because these off-the-shelf carbon fiber AFOs are sized based on the child's foot length, they can be limited in the range of children they are appropriate for but are advantageous because they are cost-effective and lightweight. They can also interface with UCBLs or SMOs if a greater measure of foot support is required.

For children with CP who are older or have more severe deficits in their gait patterns or muscle strength, carbon fiber AFOs can be custom molded. Creating a custom carbon fiber AFO allows the orthotist to fully customize the amount of support provided by the orthosis. Custom-molded carbon AFOs provide an intimate fit, improved control of deformity, and increased comfort along with energy storage and return. These types of AFOs are more costly and some designs are unable to be modified significantly to accommodate a child's growth. Therefore, use of custom-molded carbon fiber AFOs should likely be limited to the most severe cases, or for older children with CP whose growth has slowed.

Other design advances for AFOs include new ankle joints that provide a wider range of support and adjustability for children who have changing needs. Many of these ankle joints feature an anterior and/or posterior channel that provides individual assistance to weak dorsiflexors or plantar flexors. Others block motion in 1 direction but allow movement in the other direction. This property allows fine-tuned adjustments to the amount of support or ROM provided by the AFO, should the patient's goals or physical capacity change while using the orthosis. Added orthotic bulk is a disadvantage of using mechanical ankle joints.

Although advances in materials and componentry have increased the options for orthotic design, it is important to keep in mind that these advances cannot typically

**Table 1**
**A summary of gait pattern, recommended orthotic intervention, and considerations**

| Gait Pattern | Orthosis Options | Goals of Orthosis | Keys to Success |
|---|---|---|---|
| Equinus | HAFO<br>Rigid PLS<br>SAFO | • Provide swing phase clearance<br>• Allow ankle DF as available | • Appropriate evaluation of ankle DF ROM with midfoot position considered<br>• Strong soft tissue support to the midfoot within the AFO |
| Jump | Rigid PLS<br>SAFO | • Provide swing phase clearance<br>• Accommodate existing plantar flexion contracture<br>• Minimize/eliminate compensatory dorsiflexion at the midfoot<br>• Reestablish function of the PF-KE couple | • Appropriate evaluation of ankle DF ROM with midfoot position considered<br>• Strong soft tissue support to the midfoot within the AFO<br>• Proper alignment of the AFO within the footwear<br>• Adequate stiffness to increase knee extension |
| Apparent equinus | SAFO<br>FR-AFO | • Provide swing phase clearance<br>• May reestablish heel-first initial contact<br>• Restrict unwanted/excessive tibial progression<br>• Reestablish function of the PF-KE couple | • Appropriate consideration of severity of spasticity<br>• Proper alignment of the AFO within the footwear<br>• Complementary interventions<br>• Adequate stiffness to increase knee extension |
| Crouch | FR-AFO | • Minimize demand on the quadriceps through reestablishment of the PF-KE<br>• Prevent further progression of lever arm dysfunction | • Appropriate evaluation of ankle DF ROM with midfoot position considered<br>• Consideration of orthopedics for transverse plane bony deformity<br>• Strong soft tissue support to the midfoot within the AFO<br>• Proper alignment of the AFO within the footwear<br>• Adequate stiffness to increase knee extension<br>• Complementary interventions |

*Abbreviation:* DF, dorsiflexion.

overcome the presence of spasticity and plantar flexor contractures. Proper AFO alignment, consideration of ankle dorsiflexion ROM, and complementary management are necessary for most children with CP regardless of the materials or componentry used in the orthotic design.

## SUMMARY

Appropriate AFO prescription in ambulatory bilateral CP is driven by the integrity of the PF-KE. Successful AFO prescription requires interaction with complementary interventions. The AFO must accommodate the knee-extended, ankle-isolated, dorsiflexion ROM to optimize knee extension and midfoot integrity. AFO-FC modifications are

necessary to reestablish normal gait function and alignment in AFOs designed to improve walking in CP (**Table 1**).

## DISCLOSURE

The investigators have nothing to disclose.

## SUPPLEMENTARY DATA

Supplementary data related to this article can be found online at https://doi.org/10.1016/j.pmr.2019.09.007.

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