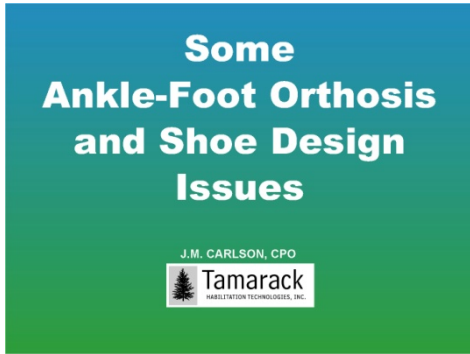
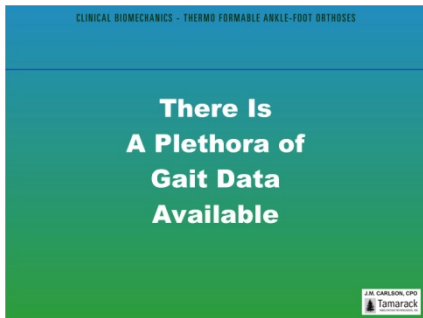


Some Ankle-Foot Orthosis and Shoe Design Issues
 J. Martin Carlson, MS (Engr.), CPO



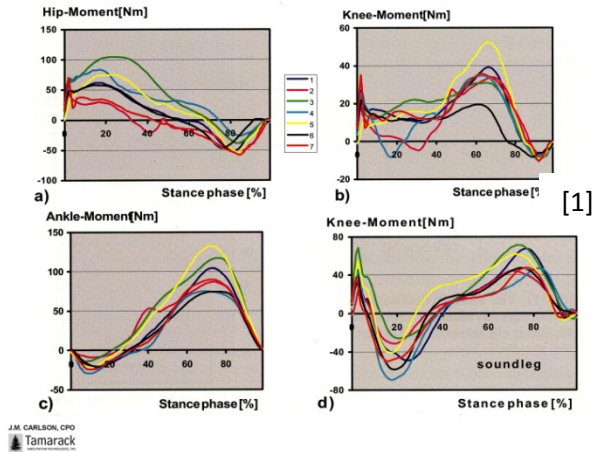
Both direct observation of what is provided and what is published in premier orthotic prosthetic journals indicate a significant level of disconnect between gait biomechanics and the design of orthotic footwear (the AFO & shoe combination). There is a huge opportunity to provide better patient benefit if a firm awareness of gait mechanics is kept in mind as we provide FO's, AFO's and shoes. The goal of this lecture series is to help orthotic and pedorthic practitioners acquire the habit of using orthosis and shoe design options to help optimize gait.

The following design vs. gait analyses are very straightforward and should contain no surprises to the well educated practitioner. The surprise is that we have some wide-spread orthotic "design habits" which fly in the face of biomechanics common sense.



This program is not intended to be an exhaustive explanation of what is happening in

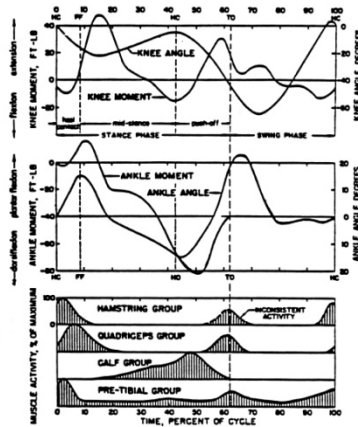
all the muscles in all three planes. There is a plethora of such information [1,2,3] which contains far more detail than we can keep in mind as we visually assess a patient's gait in clinic.



External Force

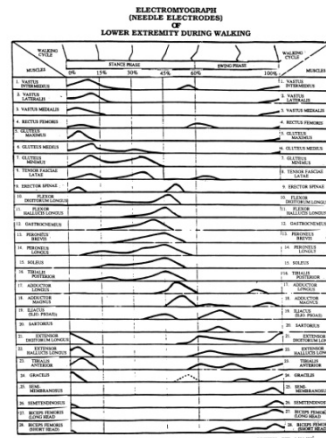
[2]

Internal Response



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[3]



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CLINICAL BIOMECHANICS - THERMO FORMABLE ANKLE-FOOT ORTHOSES

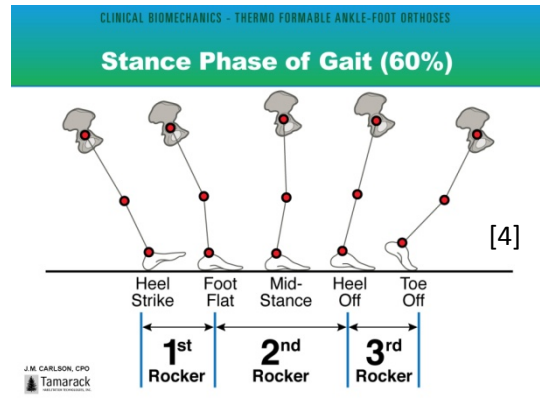
Will focus on building familiarity with a small number of gait mechanics basics I have found clinically useful

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The focus will be on a small number of gait mechanics basics, mostly in the sagittal plane, which can be kept in mind as we observe and think about what we are doing for our patient.

It is very helpful to think of the stance phase as a

series of three “rocker” motions. [4] During “First Rocker” the foot and ankle are rotating about (rocking over) the point of initial contact. (For practical reasons, we will be discussing what happens in ordinary heel-to-toe gait.) It is good, right now, to recognize that the location of initial contact depends on the shape and thickness of the heel of the shoe. Also, depending on the shape of the heel, that point may or may not move anteriorly as the forefoot pivots downward. Already we are beginning to visualize how we might affect the stability and smooth efficiency of gait by how we shape the heel of the shoe.



The “First Rocker” stage ends when the foot/shoe comes flat on the walking surface, and that event marks the beginning of “Second Rocker”. During “Second Rocker” the tibia is rotating anteriorly over a relatively stationary ankle axis and this stage ends when the heel begins to rise. “Third Rocker” takes over at that point as the hind foot and ankle begin to rise in an arc defined by an axis of rotation in the region of the metatarsal heads. Again, we must consider and try to visualize how this rocker axis is affected by stiffness and shape characteristics of the orthosis and footwear. Third Rocker ends when the toe of the footwear breaks contact with the walking surface.

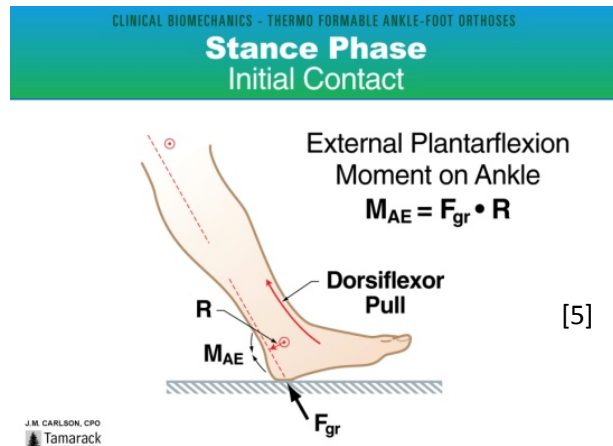
CLINICAL BIOMECHANICS - THERMO FORMABLE ANKLE-FOOT ORTHOSES

Sagittal Plane Barefoot

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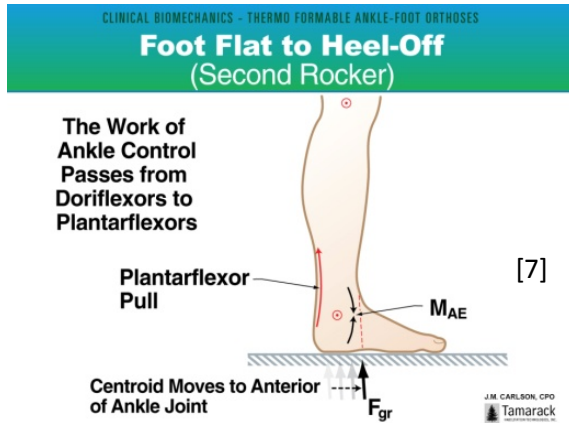
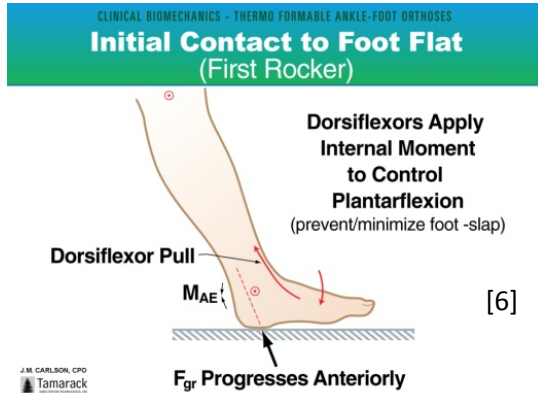
We will proceed by looking at the mechanics of barefoot walking

gait in the Sagittal plane. The floor reaction force occurs under the calcaneus and, in most cases, inertial forces cause that force to be somewhat posteriorly directed. [5] The vector line of action passes a bit posterior of the ankle joint and the dorsiflexor muscles must resist that externally applied moment in order to control forefoot descent toward foot-flat. The effort demanded of the dorsiflexor muscles during



barefoot First Rocker is directly proportional to the moment “R” which is the perpendicular distance between the ankle axis and the line of action of the floor reaction force.

~Barefoot Gait

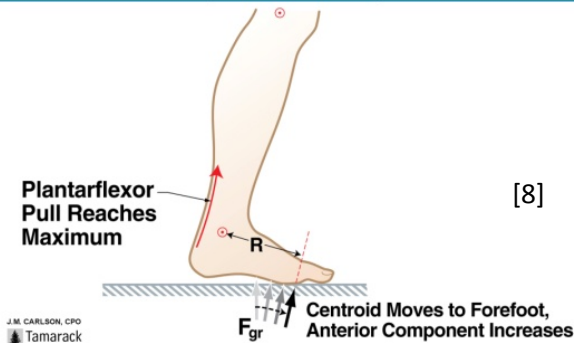


In the barefoot case, [6] the heel pad compresses and the area of contact spreads anteriorly. As this happens, of course, the centroid of the floor reaction also migrates closer to the ankle axis. This reduces the demand on the dorsiflexors as the forefoot approaches the walking surface.

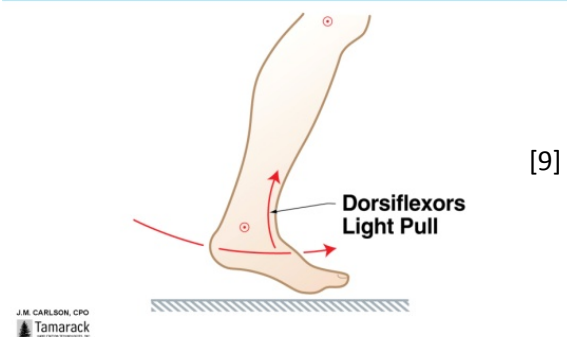
During Second Rocker, weight-bearing occurs across the entire plantar surface of the foot. [7]



As the body advances over the foot, the centroid of that distributed force quickly moves anteriorly and the plantarflexor muscles must now be the means for ankle stability.



As the heel begins to lift, initiating Third Rocker [8], the entire floor reaction is focused at the metatarsal heads and toes. The plantarflexor pull is at a maximum during the final phase of Third Rocker because the floor reaction force is operating at a long anterior lever location and because the plantarflexors are propelling the body upward and forward. [9]



Swing phase requires only light duty from the dorsiflexors to create toe clearance as the foot swings forward.

CLINICAL BIOMECHANICS - THERMO FORMABLE ANKLE-FOOT ORTHOSES

How Ankle-Foot Mechanics Are Altered By Footwear

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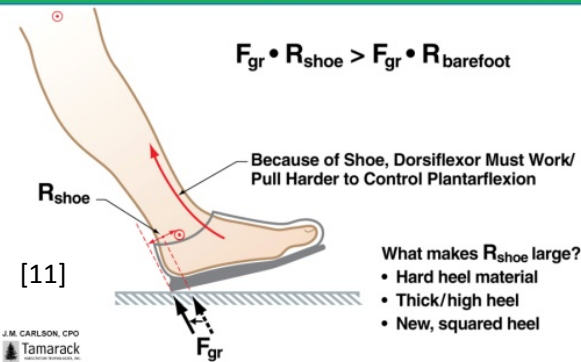
~How Ankle-Foot Mechanics are Altered by Footwear

Now we will consider and compare how the presence and design of footwear impacts muscle-joint interaction. [10, 11] Virtually all shoes, other than moccasins, displace the initial ground reaction force vector posteriorly.

This places a greater demand on the dorsiflexors. This negative effect is greater when the shoe heel is rigid, when it is thick and when it protrudes posteriorly as it does in

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Initial Contact



for a moment what happens when First Rocker is not accompanied by ankle plantarflexion. This is the case when the ankle is fused or an orthosis blocks plantarflexion. The plantarflexion moment during First Rocker must be resisted at the level of the knee. If quadriceps power is marginal, knee stability may be an issue or the quads will experience fatigue pain.

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How Can We Compensate For Loss of Plantarflexion During First Rocker?

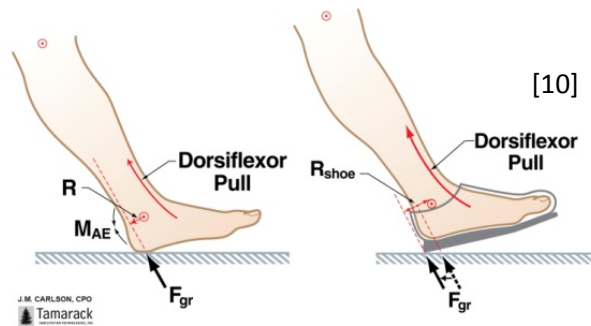
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can be accomplished most simply by deeply beveling the heel of the shoe. [12]

However, these negative consequences may be minimized by ensuring a more anterior floor reaction force. This

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Initial Contact



the Wingtip style dress shoe. Most of the high heels on cowboy boots and women's dress shoes are canted anteriorly to minimize the muscle coordination and discomfort caused by the altered First Rocker mechanics.

Now consider

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Consider Consequences of:

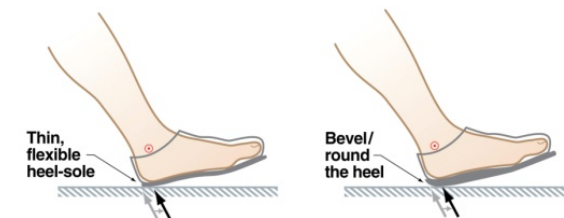
- Fused / Rigid Ankle Joint
- AFO with Plantarflexion Stop at 90°
- AFO with Rigid Ankle

(During First Rocker)

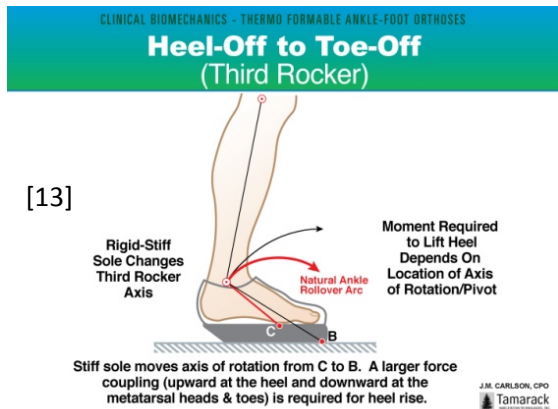
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How Can R_{shoe} Be Decreased?



When ankle motion is not blocked, the initial and mid portions of Second Rocker proceed unaffected by



[13]

footwear. However, the forces and energy expended during the latter

portion of Second Rocker are greatly affected by the thickness, flexibility and shape of the shoe sole. (In later diagrams we will also see how orthosis design impacts Second Rocker effort.)

This diagram [13] illustrates how a more rigid sole causes the ankle to arc steeper and higher during Third Rocker. This requires a greater energy input; more forefoot force during the latter portion of Second Rocker to initiate heel rise. That greater force and energy input carries through into Third Rocker to accomplish the higher vault.

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Second Rocker

- Heel and Sole Design (flexibility, thickness, shaping) and
- Ankle Range of Motion

Both Determine Duration and Forces

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Consider Various Patient Factors:

- Rigid M-P Joints Or Painful Extension
- Ulcers or Tenderness Under Metatarsal Heads

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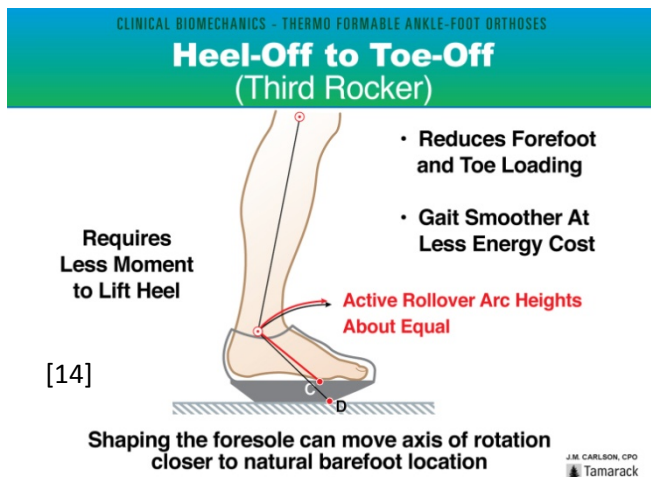
This is a very large consideration in a variety of patient conditions: If M-P joints are rigid or painful on extension; loss of sensation or ulcerations of the

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- Arthritic / Painful Ankle Joint
- Loss of Sensation

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forefoot and/or toes; arthritic foot & ankle joints; or, weakness in a combination of the hip, knee and ankle motors. These are conditions where it is extremely important to minimize the effort needed to initiate and proceed through Third Rocker. Failure to minimize that anterior



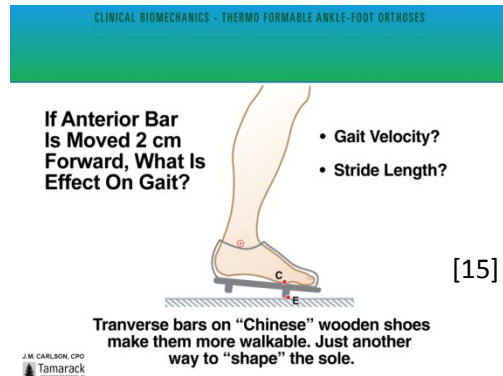
[14]

lever arm (and vaulting energy) will cause patients to externally rotate the limb. This gets the excessive anterior support “out of the way” but amplifies other problems such as knee valgus.

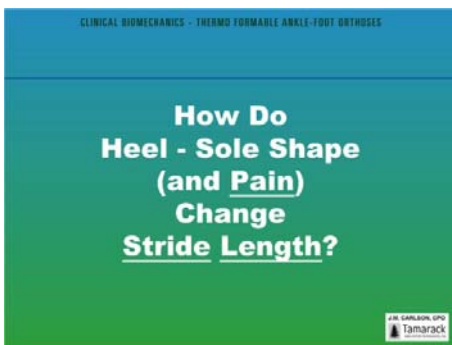
In most cases the negative effects of a thick/rigid sole may be minimized with an anterior bevel to move Third Rocker center of rotation back to a location near the metatarsal heads. [14] That normalizes the ankle roll-over arc and reduces forces on the metatarsal heads and toes. Several

things must be noted at this point:

1. As Third Rocker rotation of the shoe, foot and ankle proceeds, the toe of the (bevel-rockered) shoe descends toward the floor. If the sole build-up is insufficient, the shoe toe comes into contact very early in Third Rocker and the benefit of the bevel is lost from that point on. So, if the sole is relatively rigid, the sole build-up must be thick enough so that shoe toe contact with the floor comes late in Third Rocker, with minor effect.
2. If toe extension ROM permits, the toe of the shoe may be turned upward a bit to help delay/avoid forceful toe contact with the floor. This assumes the use of a full length steel shank imbedded in the sole.
3. A gently arced roll-over is not as effective as a plane bevel because if the fore sole is merely rounded, the line of sole contact proceeds forward immediately rather than remaining at the dihedral angle. You need to be able to picture these things in our minds eye.

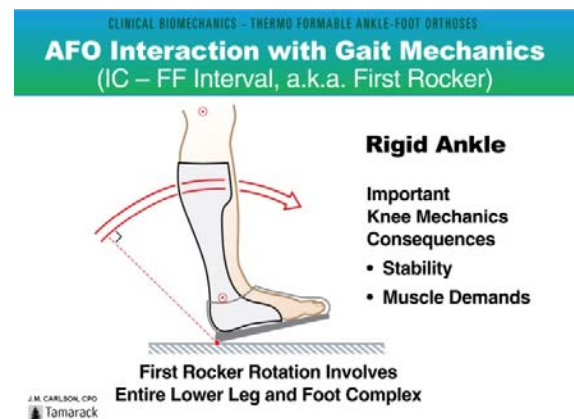


To experience the effect some of these things have on gait, firmly attach one of your old shoes to a rigid plate, try walking. Then fasten some transverse bars under the plate/board and see how that changes your walking ease and comfort. [15]



Of course a rigid sole works just fine during late Second Rocker and Third Rocker if there is no restraint of anatomical heel rise. [16]

If force on the metatarsal heads and/or toes causes pain, the tendency will be to abbreviate Third Rocker by shortening swing phase and stride length on contra-lateral side. The same thing happens when you modify a shoe sole to reduce forefoot loading.



~ *Interaction of AFO Design Features and Gait Mechanics*

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Shoe Considerations...

- Cushion or Bevel Heel

AFO Considerations...

- Ankle Joint with Plantarflexion Stop... Same as Rigid Ankle During This Stance Interval

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Now, let's consider how AFO design variations relate to the mechanics of gait. Many AFO's are designed to prevent plantarflexion. [17] It was noted earlier

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AFO Considerations...

- Ankle Joint with Plantarflexion **Allowed** (Dorsiflexion Assist for Swing Phase Toe Clearance)

BUT
Not Too Strong to Prevent IC Plantarflexion

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how this increases demands on the knee extensor muscles and coordination. Many patients adapt quite easily but those who lack quadriceps strength and/or good coordination need the shoe heel modification (beveling or cushioning) mentioned.

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AFO Interaction with Gait Mechanics
(IC – FF Interval, a.k.a. First Rocker)



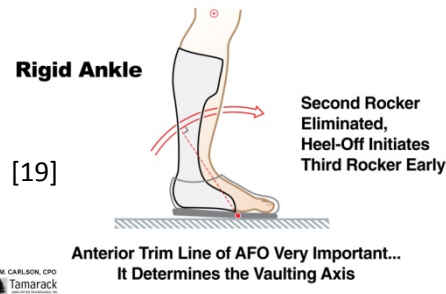
In flaccid paralysis cases, peroneal palsy, for instance, it is not necessary to totally block plantarflexion during the stance phase of gait. The dorsiflexion-assist type ankle joints can provide what is needed for swing phase and still allow the quick plantarflexion needed for a near-normal First Rocker action. [18]

The stage, which depends on ankle motion, normally represents about 70% of the stance phase of gait. If the AFO is designed to prevent/block dorsiflexion as well as plantarflexion, Second Rocker is eliminated altogether. [19]

The Second Rocker

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AFO Interaction with Gait Mechanics
(Heel-Off)



So, we need to design for a quick, efficient transition from First Rocker straight into Third Rocker. For this, we must again consider the anterior support lever arm. The anterior border of the AFO should terminate proximal of the metatarsal heads and the shoe sole should be flexible. The alternative would be the shoe sole build-up and toe bevel modifications noted earlier will help.

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Excessively Long Anterior Trim Line
A Common Design Error In the U.S. and Many Other Parts of the World

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It is a customary orthotic practice in many parts of the world, including many practitioners in the US, to routinely extend the plantar portion of the AFO to the Sulcus or even to the ends of the toes. This is one of the two most common, serious AFO design errors the world over. There are a few valid reasons to trim at the sulcus or toes end. However, unless there is specific reason to go to longer, the trim should be proximal to the metatarsal heads. Terminating the orthosis proximal to



the metatarsal heads leaves the foot and shoe free to flex naturally at and under the metatarsal heads.

This diagram [20] illustrates how significantly the ankle roll-over arc is affected by the anterior trim line. The upward deviation of the ankle arc demands/requires increased energy and coordination from the patient.

Excessive anterior support often causes the patient to externally rotate the foot during first and/or second

rocker. That maneuver reduces the line-of-progression length of anterior support they must vault over. This effect can be most reliably observed in children with Myelomeningocele. External rotation of the feet is, unfortunately, accompanied by an exaggerated tendency for greater knee valgus.

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Length of AFO:

- Becomes Critical in HO-TO Interval (Third Rocker)
- Longer AFO (More Anterior Trim Line) Delays Heel-Off and Requires More Energy (Greater Force and/or Forward Inertia)

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It is interesting to note that in prosthetic practice we are very “tuned in” to the importance of providing the optimum level of anterior roll over resistance...not too much-not too little. We need, as orthotists to apply the same level of awareness of that design variable. It is really a bit embarrassing that so many in our profession should need such a fundamental thing as this pointed out.

Some orthotists defend the extended trim lines by noting that they make that extension thin and flexible. Even those thin extensions add some toe-break resistance and should be avoided unless there is a specific, significant benefit. A secondary consideration is that the extended trim line takes space in the forepart of the shoe. An orthosis which terminates proximal to the metatarsal heads fits easily into a greater variety of footwear without the need to make room by removing the insole.

~Some Special Pediatric Considerations

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Pediatric Considerations in Orthotic Service

- Deformity Progression
- Growth and Replacement

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Designing orthoses for growing children requires us to consider several factors very important to that age

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- Bone Strength Considerations
- Mobility & Child Development
- Independence & Development
- Family Factors

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group. Those issues are: Pediatric potential for rapid deformity progression; adjustment and replacement needs; long bone weakness (when weight-bearing time is limited); and mobility effect on child development; and family factors.

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Deformity Progression

- Soft Tissue Dimensions Change Very Rapidly (difficult to reverse)
- Osseous Changes Not As Rapid (virtually impossible to reverse)

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~Potential for rapid deformity progression

Adult bodies do undergo a constant process of cell replacement and structural remodeling. However, in physically growing children, cell turnover has a minor effect compared to the dynamic cell generation changes in both soft and osseous tissues. Growth of all the musculoskeletal components is strongly affected by joint positional and bone loading factors (frequency and duration). These pediatric factors create a potential for rapid deformity development and progression.

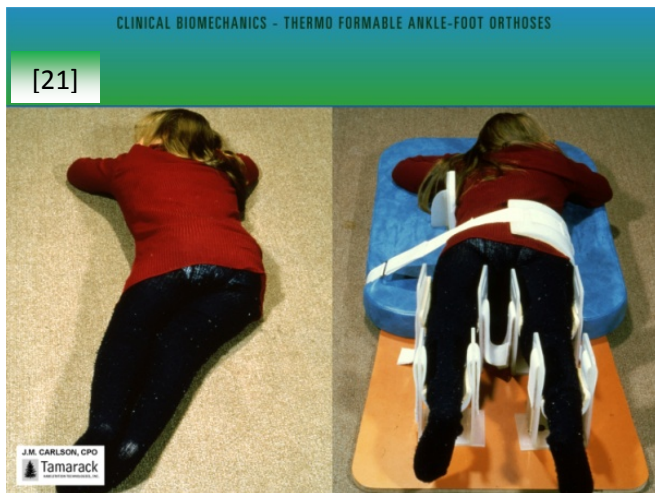
The orthotist who keeps this in mind will design for early and aggressive orthopedic support to preserve optimum joint alignment and range of motion. Skillful, persistent orthotic management throughout the growing years will contribute greatly to achieving full growth with minimal orthopedic problems going into adulthood.

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Deformity Progression

- Maximize Corrective Orthopedic Support
- Take Full Advantage of Flexibility of Remaining Growth (CP child example will be show later)

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The need to preserve hip, knee and ankle ROM seems to be clearly and broadly recognized, and approached with varying degrees of success. One of the opportunities often overlooked is what can be achieved during nighttime hours. This is a perfect time, while the child is asleep and not mobile, to keep muscles and tendons at

full length or on moderate stretch...joints in optimum alignment. This can be inexpensively done with rather simple recumbent support orthoses (RSO's). [21] These are usually designed to maintain knee and hip extension and resist hip rotation deformities. If joint alignment is not managed during nighttime hours, the growth and development process has

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Hip and Knee Deformities In Severely Impaired Children Should Be Aggressively Managed to Avoid Expensive, Difficult, Long-Term Care

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about 10 hours uninterrupted time to consolidate contractures every night. These are a couple of examples of recumbent support orthoses (RSO's). They are designed to resist the malalignment which gravity and contractures naturally tend to create and maintain while the child is recumbent.

Do not make the mistake of thinking that orthopedic deformities of the lower limbs are unimportant in non-ambulatory children. Hip and knee deformities can make bathing and toileting care very difficult, can limit both recumbent and seating positioning options to the point where pressure ulcers are a constant threat/issue. [22]



A joint which is

seldom well-managed in growing ambulatory children is the sub-talar joint. This is a very important joint in preserving a mobile, well aligned foot for upright mobility. The most common mistakes are of two types.

The first of these is not recognizing the limitations of any orthosis to stretch the very powerful

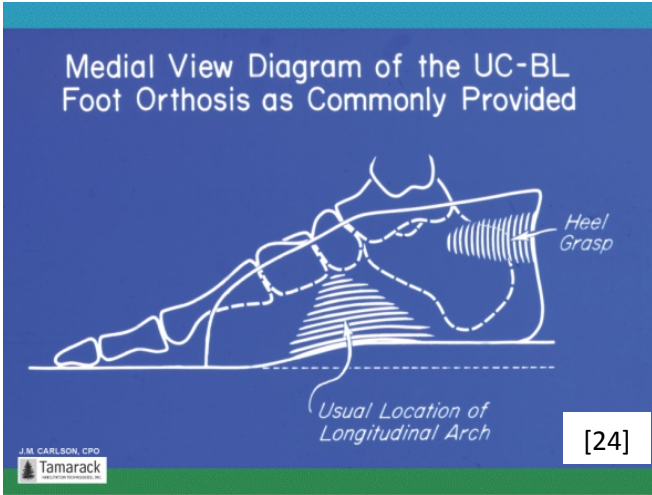
plantarflexor muscle group. This is best illustrated by considering the child with Cerebral Palsy who ambulates with difficulty. These children typically have a history of elevated muscle tone resulting in a consistently plantarflexed ankle position. Plantarflexor tone is typically elevated by the stimulating effects of vertical weight-bearing and the demands of balance control as well as a variety of external stimuli. The cast for an AFO should be taken in a passively controlled subtalar neutral alignment and with only moderate passive stretching of the Gastrocnemius-Soleus muscle group. The term "first catch" is often used to describe where passive dorsiflexion effort should stop when casting for the orthosis. To expect more correction from an orthosis will only result in a very high tendency to collapse the subtalar joint and produce excessive loading on soft tissue; on or near the navicular medially, and on the distal lateral aspect of the Calcaneus. In addition to the aggressive subtalar joint support under the Sustentaculum Talus, AFO's for these kids must have a very effective instep [23] strap to maintain the heel in its proper position in the orthosis. The instep strap must be anchored for maximum instep wrap-around and so that



the heel is pulled obliquely down and back into the depth of the heel cavity of the orthosis.

The combination of: Maintaining subtalar neutral and minimizing initiation of plantar flexor contraction, helps to reduce the frequency of extensor spasming and maintain a more quiet muscle tone throughout the child's body. This has proven to be of value even for non-ambulatory CP children.

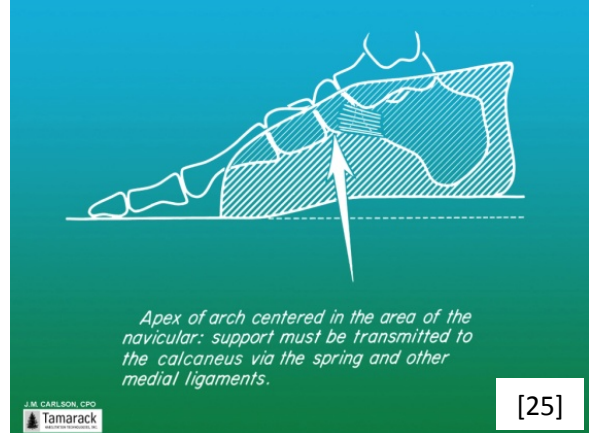
These remarks about the orthotic design needs of children with CP (the most common pediatric impairment diagnosis) do not apply to many other significant diagnoses, such as Spina Bifida, for instance, which will be mentioned more later.



[24]

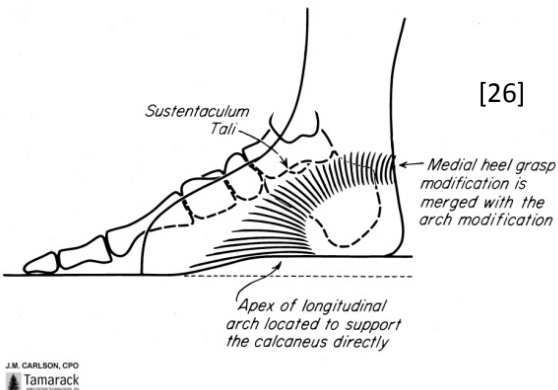
The second common mistake is to believe that valgus collapse of the subtalar joint is effectively prevented by supporting the longitudinal arch. Standard arch contours apply stabilizing support to mid foot areas. [24] That requires medial ligaments to transmit neutral alignment stability back to the subtalar joint components. That is not efficient and in time those ligaments will stretch, further jeopardizing structural

integrity of the hindfoot. [25]



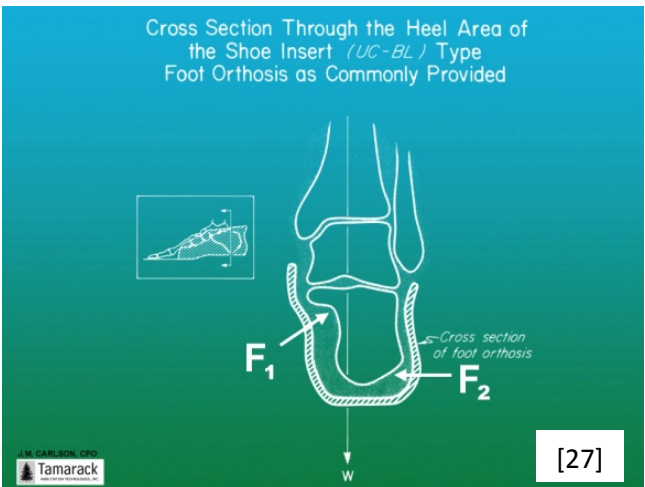
[25]

Effective, efficient support of the subtalar joint is best provided by firm support directly under the Sustentaculum Tali. This requires aggressive and precise support in the area depicted. [26] The arc of support begins broadly at the midline of the plantar surface just anterior of the calcaneal medial tubercle. It wraps up the medial side of the hindfoot coursing between the antero-medial aspect of the calcaneal tuberosity and the Navicular. Then the support becomes much



[26]

1



[27]

CLINICAL BIOMECHANICS - THERMO FORMABLE ANKLE-FOOT ORTHOSES

Growth and Replacement

- Look At Function
- Look At Skin

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less aggressive as it arcs posteriorly distal to the medial malleolus. The calcaneus must, of course, be stabilized by a containment counter-force along the distal lateral aspect of the calcaneus. [27]

Effective pediatric AFO design requires attention to design details.

~Adjustment and Replacement

Growth adjustment and replacement are obvious issues in pediatric orthotics and there is a great variation in how parents and caregivers approach this. This issue is probably best approached with an ordered inquiry:

- Is the orthosis continuing to provide the upright stance, gait and joint benefits intended?
 - If yes – then specific growth related problems such as pressure areas should be corrected by re-contouring as needed.
 - If no – then a fundamental analysis should occur to determine if the problem is simple outgrowth or is a design change needed due to the child's increasing size or development

Do not automatically replace an orthosis when it has served a certain length of time or because toes look like they are protruding a certain distance out the front of the orthosis. The most important foot support area is the posterior half of the foot section. If that is still doing a good job of maintaining sub-talar neutral without skin problems (except where easily relieved) the AFO probably does not yet need to be replaced.

~ Long bone weakness in child paraplegics (Myelomeningocele)

CLINICAL BIOMECHANICS - THERMO FORMABLE ANKLE-FOOT ORTHOSES

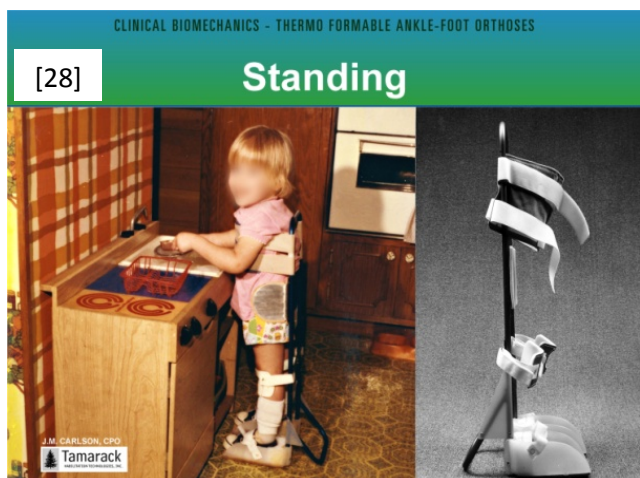
Bone Strength Considerations

- Depends on Regular Loading (femur & tibia)
- Twice Per Day Weight Bearing

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The long bones of the lower limbs, especially the femurs, tend to lose mineralization and strength if they do not experience frequent weight-bearing. It

is important to use whatever means is practical to achieve multiple daily periods of upright weight-bearing during the growing years. A simple, unjointed, crutchless standing orthosis affords a quick-in and quick-



out way for busy families to provide some periods of weight-bearing each day. [28] This is an in-expensive way to add some quick, easy standing periods in addition to (or instead of) more complex, time consuming orthoses (ie RGO) the child may have. The crutchless standing orthosis (CSO) has the advantage of offering hands-free standing for simple chore, play best done standing. If the CSO is of a light weight design, the child can move on hard surface by a back and forth tilt and swivel action.

~Mobility effect on child development

CLINICAL BIOMECHANICS - THERMO FORMABLE ANKLE-FOOT ORTHOSES

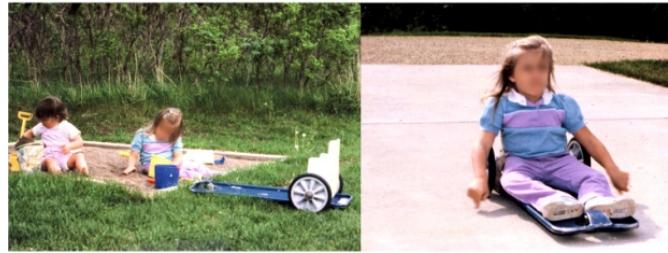
Mobility & Child Development

- Early Floor Play (non-walking mobility)
- Standing
- Walking
- Wheelchair

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Early Floor Play



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[29]

Especially during play with other children, mobility is very important. In early childhood that play is often on/near the floor or ground. During the period from 18 months to kindergarten, one of the best things we can provide a paraplegic child is a caster cart with a riding platform so close to the floor that they can independently get on and off. [29] A cart of the type shown gives the child mobile independence allowing her/him to follow or lead play from place to place.

~Family factors

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Family Factors

Minimize Family Burden
(Consistent with goal to help child be less dependent)

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Families are busy. Often both parents have full-time jobs and there are siblings who need a share of parent's time. The time required for donning and doffing orthoses should be an important consideration when deciding and designing orthoses for children. Also, anything which requires greater involvement/dependence on family members detracts from the

independence of the child. Whenever possible, design closures so that donning and/or doffing can be accomplished by the child. This is another reason for the simpler type of standing and mobility devices mentioned earlier. For instance, it will take a parent about one minute to get a preschooler into and standing in her/his CSO. Paraplegic children are able to remove themselves in about 15 seconds.

CLINICAL BIOMECHANICS - THERMO FORMABLE ANKLE-FOOT ORTHOSES

Independence & Development

Remember:
Greater Independence Develops Self-Confidence
*Help child be less dependent on others

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