
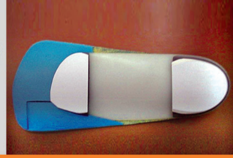


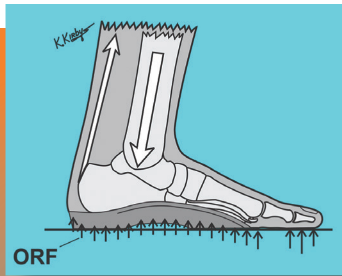

How Do Foot Orthoses Work?

Understanding biomechanics makes for better treatment outcomes.

BY KEVIN A. KIRBY, DPM

Goals and Objectives

1) To understand the history of foot orthoses.

2) To learn how foot orthosis design has changed over the years.

3) To understand the concept of the direct mechanical effect of foot orthoses.

4) To comprehend the biomechanical effects of how altering the location of ground reaction force on the plantar foot can have multiple therapeutic effects.

5) To understand the concept of the neuromotor effect of foot orthoses.

6) To learn how the central nervous system may alter the motor control of the foot and lower extremity during gait in response to foot orthoses.

7) To better comprehend how the tissue stress approach to foot orthosis therapy may be used by podiatrists to design better foot orthoses for their patients.

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*Following this article, an answer sheet and full set of instructions are provided (pg. 144).—**Editor***

I. A Brief History of Foot Orthoses

Foot orthoses have been used by the medical profession for well over two centuries in the treatment of foot and lower extremity pathologies.[1] In 1781, Petrus Camper, a Dutch physician, published one of the first books on foot deformities and their treatment in which he described placing arch-supporting orthoses into the shoes of children with flatfoot deformity.[2] In 1845, Lewis Durlacher, a British chiropodist, developed a leather foot orthosis to correct for "plantar pressure lesions" and "foot imbalances".[3] Since then, numerous other authors have described a wide range of foot orthosis designs that have been used to treat mechanically-based foot and lower extremity pathologies within the foot and lower extremity.[4–13] Today, both custom-made and pre-made foot orthoses are widely used and have been found to be therapeutically effective for many mechanically-based pathologies of the foot and lower extremity in modern scientific research.[14–40]

Even though it is clear from review of the above-listed research that foot orthoses are effective at treating various foot and lower extremity pathologies, there is still considerable debate as to how foot orthoses actually produce their impressive therapeutic results. As early as 1740, Nicolas Andry, a French physician, suggested that shoes and insoles could be modified to mechanically push the abnormally shaped foot into an improved position.[41] In 1885, Royal Whitman designed a brace with a high, stiff medial

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flange made of 18–20 gauge sheet steel to mechanically attempt to raise the medial longitudinal arch (MLA) of the foot.[42]

In the early 20th century, Dudley Morton proposed that many mechanical problems of the foot were due to a shortened first metatarsal and "hypermobility of the 1st metatarsal segment" and designed a "compensating insole" with a first metatarsal head extension to treat the condition.[6] In 1950, a New York podiatrist, Benjamin Levy, developed a cork and leather insole with a medial arch and a toe crest which became known as the Levy Mold.[8]

Then, in 1958, a California podiatrist, Merton Root, began work on his thermoplastic Root functional orthosis that had a lower MLA than many previous orthosis designs.[11] Root felt that the high MLA was not necessary and designed his orthosis with the goal of having the subtalar joint (STJ) function in neutral position and to prevent "compensation" for "rearfoot and forefoot deformities."[43]

In 1982, Richard Blake developed a highly inverted orthosis with a deep heel cup, flat rearfoot post and plantar fascial accommodation, the Blake Inverted Orthosis, to treat pronation-related symptoms.[12,44-46]

In 1992, Kirby introduced the medial heel skive technique (Figure 1), which allowed for a variable amount of varus contour to be added within the orthosis heel cup to better treat patients with symptoms caused by excessive STJ pronation moments, such as posterior tibial tendon dysfunction.[13] In 2001, Benno Nigg proposed his "preferred movement pathway model" of orthosis function, where he postulated that foot orthoses which counteract the "preferred movement path" of the foot and lower extremity will cause an increase in muscle activity and that optimally-designed orthoses will reduce or minimize muscle activity.[47]

As is evident from this short review of foot orthosis design history, orthoses have been modified continuously for at least the last two centuries in an attempt to produce a mechanical effect that treats structural abnormalities and relieves mechanically-based symptoms of the foot and lower extremity. Modifications to foot orthoses—such as heel lifts, Morton's extensions, reverse Morton's extensions, metatarsal pads, metatarsal head accommodations, medial and lateral heel skives, medial and lateral flanges, plantar fascial accommodations, rearfoot and forefoot posts, and different types and combinations of top cover materials—are just a few of the variety of customization possibilities used today in custom foot orthoses to treat patients with pathologies caused by abnormal foot and lower extremity biomechanical function.[48]

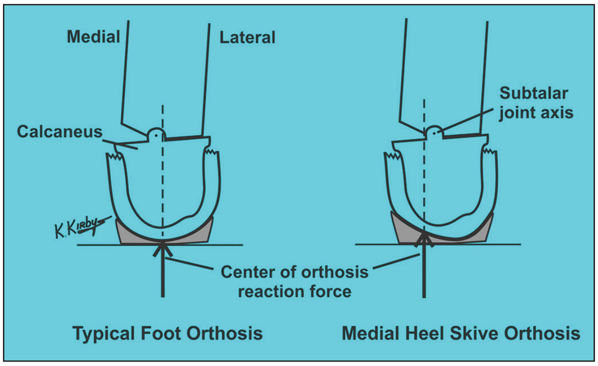

Figure 1: In a typical foot orthosis, the plantar contour of the heel of the foot is matched by the heel cup shape of the orthosis (left). However, in an orthosis with a medial heel skive (right), a varus contour is added into the orthosis heel cup to shift the center of orthosis reaction force medially on the plantar heel to increase the supination moment across the subtalar joint axis.

II. How Do Orthoses Work?

Even though it is clear from the scientific research literature that foot orthoses work well in the treatment of many pathologies, there is no general consensus within the medical and/or biomechanics research community as to how foot orthoses produce their impressive therapeutic results for patients suffering from foot and lower extremity pathologies. Currently, there are only a few theoretically coherent and biologically plausible possibilities as to how orthoses function to produce their biomechanical effects. The two most likely and logical explanations are, by one or a combination of two methods, the direct mechanical effect or the neuromotor effect.[49]

A. Direct Mechanical Effect of Foot Orthoses

The direct mechanical effect is defined as the kinetic effects (i.e., pertaining to forces and moments) and kinematic effects (i.e., pertaining to position and motion) acting on and within the foot and lower extremity which result from alterations in the location, magnitude, and temporal patterns of ground reaction force (GRF) acting on the plantar foot.[49] The mechanical contact between the foot orthosis and the plantar foot is also known as orthosis reaction force (Figure 2) and may alter either the compression and/or shearing components of GRF.[50]

To illustrate the direct mechanical effect of foot orthoses, an "anti-pronation" foot orthosis with a higher, stiffer MLA and a medial heel skive[13] commonly used to treat a patient with symptoms caused by excessive STJ pronation moments will be biomechanically analyzed. Such an "anti-pronation" foot orthosis design is commonly used to treat, for example, flexible pes planus deformity in children and posterior tibial tendon dysfunction in adults.[13,51,54]

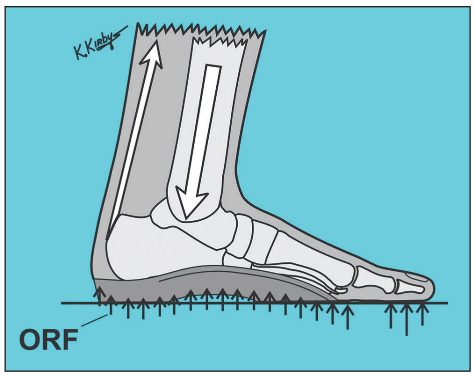

Figure 2: When a foot orthosis mechanically interacts with the plantar foot, an orthosis reaction force (ORF) is created which alters the magnitude, plantar locations and temporal patterns of ground reaction force acting on the plantar foot during weightbearing activities.

The higher, stiffer MLA of the "anti-pronation" orthosis will increase the GRF acting upon the medial midfoot and will decrease the GRF on the lateral midfoot.[52] The shift in GRF from lateral to medial in the midfoot (Figure 3), shifting some of the GRF from the

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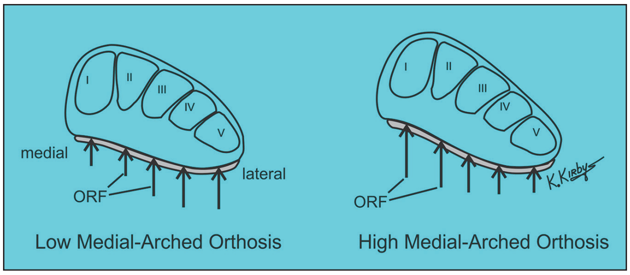

Figure 3: In these illustrations of a frontal plane cross-section of a foot at the metatarsal bases in the midfoot, a foot orthosis with a relatively flexible, low medial longitudinal arch (MLA) is seen to result in increased orthosis reaction force (ORF) on the lateral midfoot (left). However, an orthosis with a stiffer, higher MLA will shift ORF away from the lateral midfoot and to the medial midfoot (right), thus increasing the subtalar joint supination and medial longitudinal arch- raising effects of the orthosis.

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lateral longitudinal arch to the MLA, helps to reduce the amount of MLA flattening in the foot. In addition, the medial heel skive will increase the varus heel cup contour of the orthosis which will, in turn, shift GRF away from the lateral aspect of the plantar heel and toward the medial aspect of the plantar heel of the foot.[53]

An orthosis with a higher-stiffer medial longitudinal arch helps reduce the amount of medial longitudinal flattening of foot.

Increasing the GRF on the MLA with the higher, stiffer MLA and on the medial aspect of the plantar heel with the medial heel skive in the "anti-pronation" orthosis will produce a direct mechanical "anti-pronation" effect from the orthosis by altering the locations and magnitudes of GRF acting on the plantar foot.[54] The medial shift in GRF acting on the plantar heel and plantar midfoot will produce an increase in external STJ supination moment (Figure 4) and an increase in external MLA-raising moment.[55] By definition, external moments are caused by forces acting outside the body (e.g., GRF) and internal moments are caused by forces acting within the body (e.g., tension force in muscles, tendons, and ligaments).[56,57]

In other words, the medial shift in GRF on the plantar heel and plantar midfoot caused by the "anti-pronation" orthosis will produce an increased tendency for the foot orthosis to supinate the STJ. Likewise, the higher, stiffer orthosis MLA will produce an increased tendency for the orthosis to raise the MLA. The MLA and medial heel cup of the "anti-pronation" foot orthosis directly exerts increased compression force on the medial aspect of the plantar foot which, being more medial to the STJ axis, causes an increase in external STJ supination moment which will produce increased STJ supination, unless resisted by an equal or larger STJ pronation moment.[13]

Similar direct mechanical effects of foot orthoses, where the orthoses redistribute GRF from high-pressure symptomatic areas to lower-pressure asymptomatic areas of the plantar foot (Figure 5), can be seen in the effective treatment of other common pathologies such as metatarsalgia[20,36] and diabetic neuropathic ulcers.[26,27,30] Foot orthoses may also exert a direct mechanical effect in preventing the excessive bending moments that cause stress fractures within the long bones of the lower extremity (Figure 6) such as in femoral and metatarsal stress fractures.[19,24]

Foot orthoses have also been shown in numerous studies to exert a direct mechanical effect in relieving the pain and disability of medial knee osteoarthritis[58–67] and plantar fasciitis.[68–70] Therefore, the net result of the direct mechanical effect of foot orthoses is to redirect the location and direction of pushing force from the foot orthosis to alter local plantar foot pressures and/or to change joint moments that will, in turn, alter the joint position and/or joint motions of the foot that is in the same direction as the orthosis pushing force.[49,71]

B. Neuromotor Effect of Foot Orthoses

The second possible method by which foot orthoses can alter the kinematics and kinetics of gait is by their neuromotor effect. The neuromotor effect of foot orthoses is somewhat more complicated since it is mediated by the central nervous system (CNS) and is defined as the kinetic and kinematic effects on the foot and lower extremity that are caused by changes in sensory input to, and motor output from, the CNS.[49]

As a brief review, afferent inputs into the CNS of an individual may come from sensory organs within the skin, joints, muscles, tendons, eyes, inner ears, or other areas of the body.[72] The mechanical interaction of the foot orthosis with the plantar foot may cause, for example, changes in plantar foot pressures, changes in stretching of joint capsular ligaments and tendons, changes in balance, and other mechanical effects, that all have the potential to be relayed as afferent stimuli via the peripheral nervous system to the CNS. These alterations in afferent sen-

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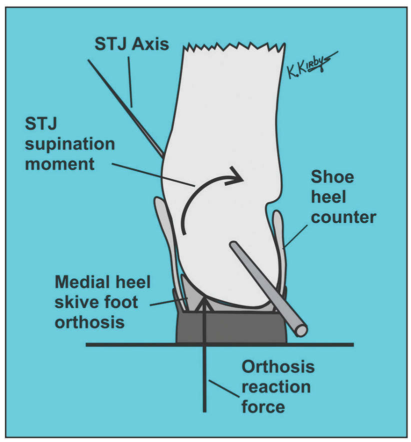

Figure 4: When an anti-pronation foot orthosis designed with a higher, stiffer medial longitudinal arch and medial heel skive is used to treat patients suffering from pronation-related pathologies, such as posterior tibial tendon dysfunction, the medial shift in orthosis reaction force from this specially-designed orthosis will increase the external subtalar joint (STJ) supination moment by increasing the orthosis reaction force medial to the STJ axis, thus improving the anti-pronation effectiveness of the foot orthosis.

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sory stimuli resulting from mechanical interaction of the orthosis with the plantar foot may, upon processing by the CNS, result in the CNS altering the magnitudes and temporal patterns of efferent motor output muscles of the foot and lower extremity during weight-bearing activities to increase the metabolic efficiency of locomotion, maintain balance and prevent injury.

Thousands of times a day, the CNS processes afferent signals from the peripheral nervous system and then sends "corrective" efferent motor stimuli to the muscles of the foot and lower extremity with the goal to optimize weight-bearing dynamics and prevent injury.[73–76]

The neuromotor effect of foot orthoses may then be illustrated by the example of an "anti-pronation" foot orthosis that has an excessively high and stiff MLA with a varus forefoot post being used in a patient with a relatively normal foot and with a normal MLA height. The clinical use of such an "anti-pronation" orthosis in a foot that is not overly pronated, nor suffering from pronation-related pathologies, will result in a large increase in external STJ supination moment that may tend to over-supinate the foot and cause the individual to experience "lateral-instability" during gait.[49]

When such an "over-varus-corrected" foot orthosis is used in a foot that does not need increased varus support to function optimally, the patient's foot will commonly undergo late midstance pronation during walking gait. The explanation for the paradoxical increase in late midstance STJ pronation during walking is that the CNS, sensing the impending lateral-instability situation, responds with increased motor output to the peroneal muscles to prevent an inversion ankle injury or a fall. In other words, the result of using a strong "anti-pronation" orthosis design in a foot which is not overly pronated may cause the CNS to respond with increased efferent output to the peroneal muscles during late midstance, causing an increased internal STJ pronation moment which, in turn, actively pronates the STJ during late midstance.[49]

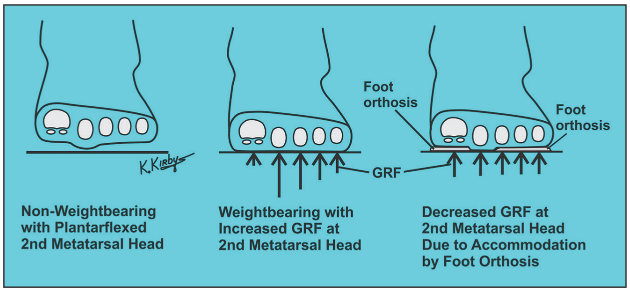

Figure 5: Foot orthoses can exert a direct mechanical effect on the plantar foot by redirecting ground reaction force (GRF) from high-pressure areas to lower-pressure areas of the plantar foot. For example, in a foot with a plantarflexed 2nd metatarsal that is non-weight-bearing, the 2nd metatarsal head will be plantarly prominent (left). When the foot becomes weight-bearing, the plantarflexed 2nd metatarsal will receive increased GRF (middle). A foot orthosis designed with an accommodation for the 2nd metatarsal head effectively reduces GRF plantar to the 2nd metatarsal head which reduces the pressure and pain from such common conditions (right).

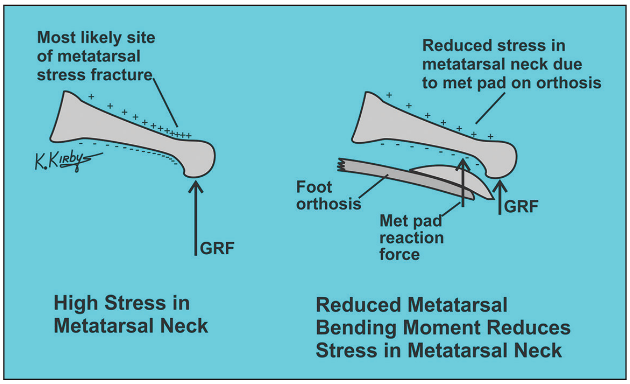

Figure 6. When the plantar head of a metatarsal bears weight and is subjected to ground reaction force (GRF), a bending moment will occur within the metatarsal shaft that will tend to bend the distal metatarsal upward, causing increased compression stress within the dorsal cortex and increased tension stress within the plantar cortex of the metatarsal shaft (left). These metatarsal cortical stresses, when of sufficient magnitude, can lead to metatarsal stress fractures. Foot orthoses can exert a direct mechanical effect on the metatarsal by the use of a metatarsal pad and/or a thicker anterior orthosis edge (right), which will increase the GRF on the metatarsal neck, decrease the GRF on the metatarsal head, and decrease the metatarsal bending moments. As a result, abnormal metatarsal shaft cortical stresses will be lessened which will, in turn, lead to a decreased likelihood of metatarsal stress fractures.

The neuromotor effect of a foot orthosis means that even though an "anti-pronation" foot orthosis may be designed to directly push the foot toward a supinated position, the CNS may respond to any excessive external STJ supination moment caused by the orthosis by increasing the pronation motion of the STJ, via peroneal muscle activation, during the late midstance phase of gait. It is very likely that these neuromotor effects of foot orthoses play a very significant role in how foot orthoses may or may not be able to change the position and/or motion patterns and/or change the forces and moments acting across the joint axes of the foot and lower extremity during weight-bearing activities.[49]

III. Tissue Stress Theory

With a full understanding of the physiological and mechanical factors that govern the direct mechanical and neuromotor effects of foot orthoses, the podiatrist will then possess an exceedingly powerful conservative treatment modality to treat a wide variety of mechanically-based pathologies within the foot and lower extremity. Using the "Tissue Stress Approach" to foot orthosis therapy, the podiatrist may specifically design custom foot orthoses to reduce the stress acting within the injured structural components of the foot and lower extremity that are causing the pain and disability.[77,78]

The Tissue Stress Approach promotes the use of numerous orthosis design variables that are now available within modern prescription foot orthosis laboratories to more effectively and efficiently design truly custom foot orthoses that will greatly improve the therapeutic success of foot orthosis therapy by directing orthosis treatment toward reducing stress on injured tissues, versus directing orthosis treatment toward "preventing compensations" for "rearfoot and forefoot deformities.[11,43,77,78]

The author's clinical experience has shown that not only is healing from injury accelerated, but other injuries may also be prevented in the

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future by judiciously using the Tissue Stress Approach to orthosis therapy. The results of the Tissue Stress Approach are better therapeutic orthosis outcomes for those podiatrists who take the time to fully understand the biomechanical principles and learn the skills necessary to use this increasingly popular method of custom foot orthosis prescription.

A clinical example of the neuromotor effect of foot orthoses is a foot orthosis that has a medial heel skive, high medial arch and forefoot varus post that causes late midstance pronation.

IV. Conclusion

Even though foot orthoses have been used for well over two centuries, and have been shown in numerous scientific studies to be therapeutically effective for a multitude of foot and lower extremity pathologies, there is still uncertainty as to how they actually work. By pushing directly on the plantar foot with varying magnitudes, in different plantar locations and with different temporal patterns, foot orthoses may push on the plantar foot to relieve high pressure areas or may push on the plantar foot to reduce internal tissue stresses or to reduce excessive or abnormal joint motions in the joints of the foot and lower extremity. However, when improperly prescribed, foot orthoses may also often cause seemingly paradoxical motions in the foot and lower extremity in directions opposite to the pushing force from the orthosis, which is most likely the result of CNS motor output over-riding the pushing effects from the foot orthosis.

Much more research is needed to add further clarity to the subject of how foot orthoses biomechanically and neurologically produce their beneficial therapeutic effects. Until then, podiatrists can at least be certain that foot orthoses, when prescribed carefully by the skilled clinician, are still one of the best conservative treatment options for patients with mechanically-based foot and lower extremity pathologies. **PM**

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SEE ANSWER SHEET ON PAGE 145.

1) Custom foot orthoses were first reported within the medical literature how many years ago?
A) 50 years ago.
B) 75 years ago.
C) 100 years ago.
D) Over 230 years ago.

2) Merton Root proposed the following ideas:
A) The foot orthosis should have a medial longitudinal arch that exactly matched the contours of the casted foot.
B) The goal of foot orthosis therapy was to reduce the stress of tissues within the foot and lower extremity.
C) The goal of foot orthosis therapy was to prevent compensations for forefoot and rearfoot deformities.
D) None of the above.

3) The direct mechanical effect of foot orthoses means the following:
A) The foot orthosis will always tend to push the subtalar joint toward neutral position.
B) The foot orthosis will change the position, motion, forces, and moments in the foot and lower extremity due to direct mechanical interaction of the foot with the orthosis.
C) The foot orthosis will change foot and lower extremity kinetics and kinematics due to central nervous system intervention.
D) The foot orthosis will work to push the foot in the direction opposite to the orthosis reaction force.

4) An orthosis with a higher-stiffer medial longitudinal arch, used in anti-pronation orthoses, does the following:
A) Helps reduce the amount of medial longitudinal flattening of foot.
B) Helps to pronate the foot in early stance phase of walking.
C) Shifts ground reaction force laterally in the midfoot.
D) Increases the external subtalar joint pronation moment acting on the foot.

5) The direct mechanical effect of foot orthoses is demonstrated by successful foot orthosis treatment of which of the following pathologies?
A) Diabetic neuropathic plantar ulcers.
B) Metatarsal stress fractures.
C) Medial compartment osteoarthritis of the knee.
D) All of the above.

6) A shift in ground reaction force more medially on the medial heel and medial midfoot with an anti-pronation orthosis will cause the following:
A) An increase in external subtalar joint supination moment.
B) An increase in external medial longitudinal arch-raising moment.
C) A and B.
D) None of the above.

7) The neuromotor effect of foot orthoses postulates the following:
A) The central nervous system may respond to the mechanical effects of a foot orthosis with varied motor control to the muscles of the foot and lower extremity that is contrary to the pushing effects of the foot orthosis.
B) The central nervous system relies on the foot orthosis to push and move the foot into the subtalar joint neutral position.
C) The peripheral and central nervous systems work together to allow normal gait patterns regardless of the pushing effect from foot orthoses.
D) Foot orthoses work to alter the position of foot joints by only mechanically pushing the foot joints in the direction of the orthosis pushing force.

Continued on page 144

8) Which of the following are true about external forces and internal forces acting on and within the foot and lower extremity?

A) External forces are those forces which act on the external surface of the body.
B) Internal forces are those forces acting within the body.
C) Posterior tibial tendon tension and plantar fascial tension are examples of internal forces.
D) All of the above.

9) When an orthosis pushes on the plantar foot, what effects can it produce?

A) A direct mechanical effect.
B) A neuromotor effect.
C) A change in the locations, magnitudes and temporal patterns of ground reaction force acting on the plantar foot.
D) All of the above.

10) A clinical example of the neuromotor effect of foot orthoses is the following:

A) A foot orthosis with a high medial longitudinal arch that pushes the medial longitudinal arch of the foot higher.
B) A foot orthosis with a metatarsal pad that reduces ground reaction force on the metatarsal head.
C) A foot orthosis that has a medial heel skive, high medial arch and forefoot varus post that causes late midstance pronation.
D) A foot orthosis with a reverse Morton's extension that reduces ground reaction force on the first metatarsal head.

SEE ANSWER SHEET ON PAGE 145.

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EXAM #7/16
Understanding the First Ray
(D'Amico)

Circle:

1.	A	B	C	D	6.	A	B	C	D
2.	A	B	C	D	7.	A	B	C	D
3.	A	B	C	D	8.	A	B	C	D
4.	A	B	C	D	9.	A	B	C	D
5.	A	B	C	D	10.	A	B	C	D

Medical Education Lesson Evaluation

Strongly agree [5]	Agree [4]	Neutral [3]	Disagree [2]	Strongly disagree [1]

1) This CME lesson was helpful to my practice ____

2) The educational objectives were accomplished ____

3) I will apply the knowledge I learned from this lesson ____

4) I will makes changes in my practice behavior based on this lesson ____

5) This lesson presented quality information with adequate current references ____

6) What overall grade would you assign this lesson?
A B C D

How long did it take you to complete this lesson?

______hour ______minutes

What topics would you like to see in future CME lessons ?
Please list :

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EXAM #8/16
How Do Foot Orthoses Work?
(Kirby)

Circle:

1.	A	B	C	D	6.	A	B	C	D
2.	A	B	C	D	7.	A	B	C	D
3.	A	B	C	D	8.	A	B	C	D
4.	A	B	C	D	9.	A	B	C	D
5.	A	B	C	D	10.	A	B	C	D

Medical Education Lesson Evaluation

Strongly agree [5]	Agree [4]	Neutral [3]	Disagree [2]	Strongly disagree [1]

1) This CME lesson was helpful to my practice ____

2) The educational objectives were accomplished ____

3) I will apply the knowledge I learned from this lesson ____

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5) This lesson presented quality information with adequate current references ____

6) What overall grade would you assign this lesson?
A B C D

How long did it take you to complete this lesson?

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