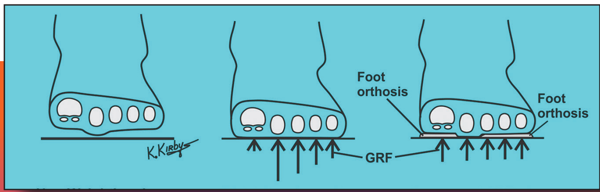

How Do Foot Orthoses Work? 2019 Edition

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. 128).—**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]

Foot orthoses have been used by the medical profession for well over two centuries in the treatment of foot and lower extremity pathologies.

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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]

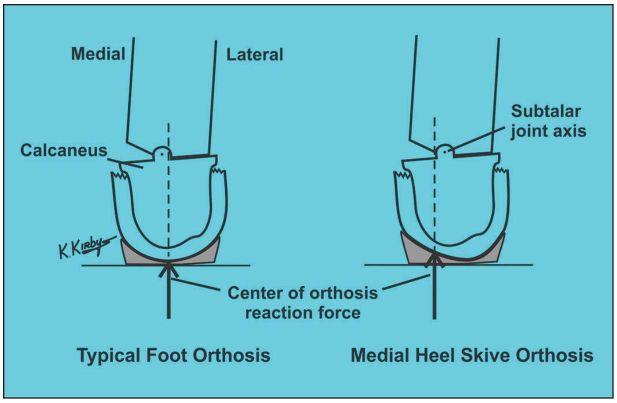

Figure 1: In a typical foot orthosis, the plantar contour of the heel of the foot is matched by the heel cup shape of the orthosis (left). However, in an orthosis with a medial heel skive (right), a varus contour is added into the orthosis heel cup to shift the center of orthosis reaction force medially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

Even though it is clear from reviewing a plethora of 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 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]

Merton Root said that the goal of foot orthosis therapy was to prevent compensations for forefoot and rearfoot deformities.

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 to have 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.[12,44,45,46] 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]

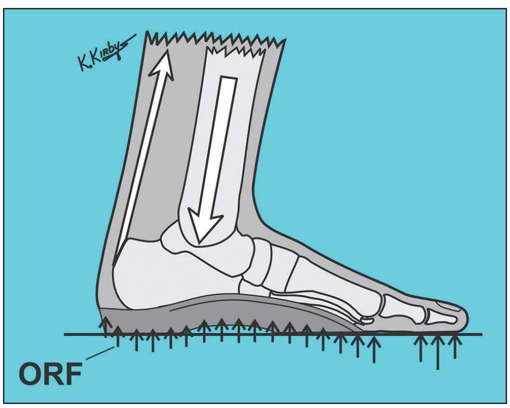

Figure 2: When a foot orthosis mechanically interacts with the plantar foot, an orthosis reaction force (ORF) is created which alters the magnitude, plantar locations and temporal patterns of ground reaction force acting on the plantar foot during weightbearing activities.

As is evident from this short review of foot orthosis design history, orthoses have been utilized and 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, heel lifts, medial and lateral heel skives, medial and lateral flanges, plantar fascial accommodations, rearfoot and forefoot posts, and different types and combinations of topcover 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.[47]

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 the-

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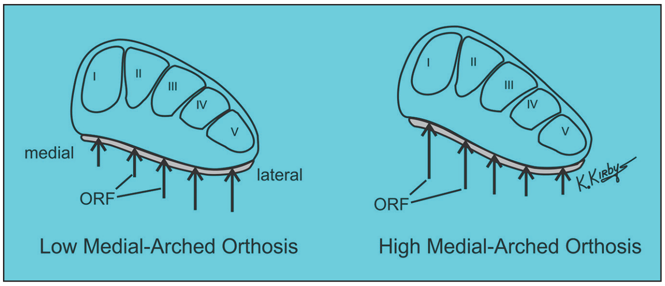

Figure 3: In these illustrations of a frontal plane cross-section of a foot at the metatarsal bases in the midfoot, a foot orthosis with a relatively flexible, low medial longitudinal arch (MLA) is seen to result in increased orthosis reaction force (ORF) on the lateral midfoot (left). However, an orthosis 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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oretically coherent and biologically plausible possibilities as to how orthoses function to produce their biomechanical effects. The two most likely and logical explanations as to how foot orthoses function to produce their clinical results is, by one or a combination of two methods, the direct mechanical effect or the neuromotor effect.[48]

A. Direct Mechanical Effect of Foot Orthoses

The direct mechanical effect of foot orthoses 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.[48] The mechanical contact between the foot orthosis and the plantar foot is also known as orthosis reaction force, or ORF, (Figure 2) and may alter either the compression and/or shearing components of GRF.[49]

To illustrate the direct mechanical effect of foot orthoses, a clinical situation of the orthosic treatment of a patient with symptoms caused by excessive STJ pronation moments will be biomechanically analyzed. The “anti-pronation” foot orthosis used in this example to treat the patient possesses a higher, stiffer MLA and a medial heel skive.[13] 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.[13,50,55]

The higher, stiffer MLA of the “anti-pronation” orthosis will increase the GRF acting upon the medial midfoot and will decrease the GRF acting upon the lateral midfoot.[51] By increasing the varus heel cup contour of the orthosis, the medial heel skive will shift GRF away from the lateral aspect and towards the medial aspect of the plantar heel of the foot.[52] In addition, by the shifting of GRF from the lateral midfoot to the MLA of the plantar foot (Figure 3), the amount of MLA flattening in the foot is also reduced. Recently, research studies using sophisticated motion analysis and biplane fluoroscopy systems have confirmed the long-held clinical belief that foot orthoses do effectively reduce MLA flattening of the foot during weight-bearing activities.[53,54]

The direct mechanical effect of foot orthoses means that 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.

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.[55] The medial shift in GRF acting on the plantar heel and plantar midfoot will produce an increase in STJ supination moment (Figure 4) and an increase in MLA-raising moment, both of which are “external moments”.[56] 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).[57,58]

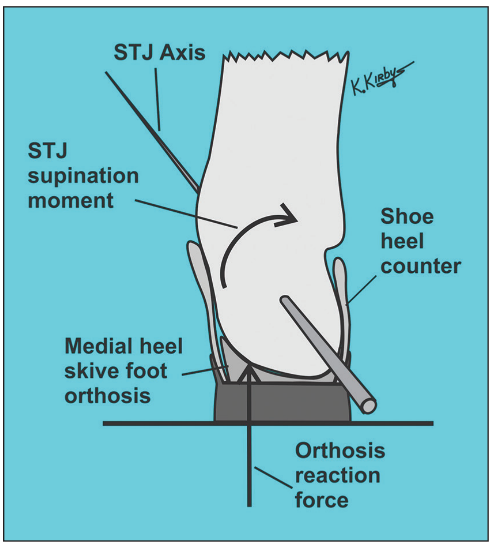

Figure 4: When an anti-pronation foot orthosis designed with a higher, stiffer medial longitudinal arch and medial heel skive is used to treat patients suffering from pronation-related pathologies, such as posterior tibial tendon dysfunction, the medial shift in orthosis reaction force from this specially-designed 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.

In other words, the medial shift in GRF on the plantar heel and plantar midfoot caused by the “anti-pronation” orthosis will produce an in-

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creased tendency for the foot orthosis to supinate the STJ or reduce pronation of the STJ. Likewise, the higher, stiffer orthosis MLA will produce an increased tendency for the orthosis to raise the MLA, or reduce flattening of the MLA. The MLA and medial heel cup of the "anti-pronation" foot orthosis directly exerts increased compression forces onto the medial aspect of the plantar foot which, being more medial to the STJ axis, causes an increase in STJ supination moment, which will either produce an increase in STJ supination or a decrease in STJ pronation during weight-bearing activities.[13]

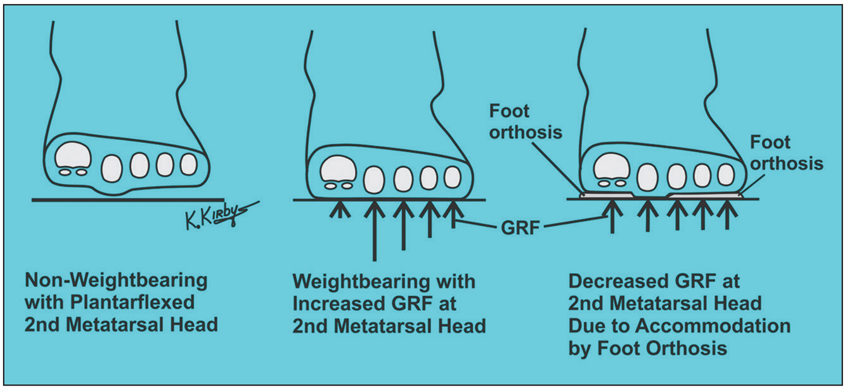

Figure 5: Foot orthoses can exert a direct mechanical effect on the plantar foot by redirecting ground reaction force (GRF) from high-pressure areas to lower-pressure areas of the plantar foot. For example, in a foot with a plantarflexed 2nd metatarsal that is non-weight-bearing, the 2nd metatarsal head 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).

Similar direct mechanical effects of foot orthoses, where the orthosis redistributes GRF from high-pressure symptomatic areas to lower-pressure asymptomatic areas of the plantar foot (Figure 5), can be seen in the effective foot orthosis 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 can cause stress reactions and fractures within the long bones of the lower extremity (Figure 6) such as in the femur, tibia, and metatarsals.[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,[59-69] plantar fasciitis,[70-73] patellofemoral pain,[38,40,74] and low back pain.[75] In addition, foot orthoses have recently been shown in two large prospective studies on military recruits to reduce the incidence of lower extremity injuries during basic training.[39,76]

Therefore, the net result of the direct mechanical effect of foot orthoses is to alter the set of locations, temporal patterns, and directions of the pushing forces from GRF that would normally occur from weight-bearing on a flat surface (e.g., ground, shoe insole) and convert them into another set of locations, temporal patterns, and directions of plantar pushing forces. The ultimate goal of these direct mechanical effects of foot orthoses is to alter the plantar foot pressures and/or plantar foot forces in such a fashion that any pathological internal forces and moments acting within the foot and

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

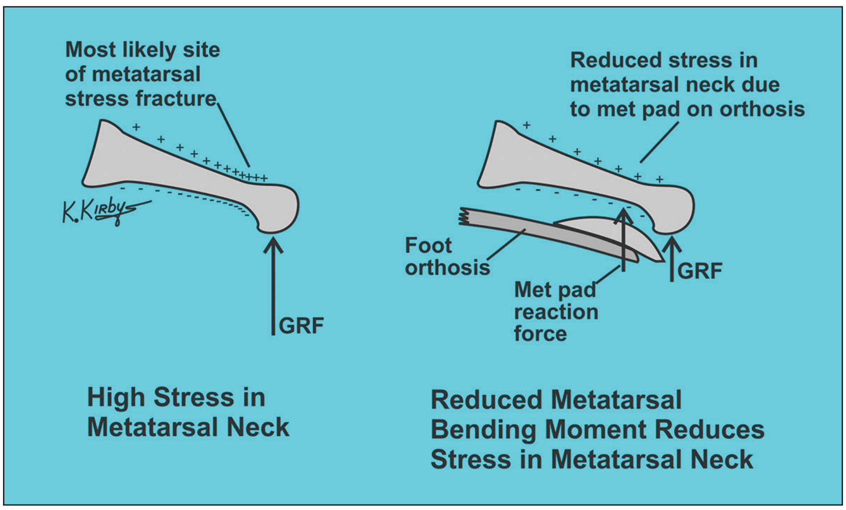

Figure 6: When the plantar head of a metatarsal bears weight and is subjected to ground reaction force (GRF), a bending moment will occur within the metatarsal shaft that will tend to bend the distal metatarsal upward, causing increased compression stress within the dorsal cortex and increased tension 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.

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lower extremity that are causing pain are reduced by the plantar forces from the foot orthosis.[48,77]

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.[48]

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.[78] 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, 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 sensory 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 signals to the muscles of the foot and lower extremity during weight-bearing activities to decrease the metabolic energy used during locomotor activities, to maintain balance and to prevent injury. Thousands of times a day, the CNS processes afferent signals from the peripheral nervous system and then sends "corrective" efferent motor output to the muscles of the foot and lower extremity with the goal to optimize weight-bearing dynamics and prevent injury.[79-82]

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.

The neuromotor effect of foot orthoses postulates that 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.

The neuromotor effect of foot orthoses may also be illustrated by the example of an "anti-pronation" foot orthosis: an excessively high and excessively stiff MLA with a varus forefoot post that is, instead of being used in an excessively-pronated foot as in the last example, is rather 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 STJ supination moment that may tend to cause the foot to over-supinate and cause the individual to experience "lateral-instability" during gait.[48]

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 most logical explanation for the paradoxical increase in late midstance STJ pronation during walking with a foot orthosis that has excessive "pronation-control" features is that the CNS, sensing the impending lateral-instability situation from the orthosis, 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, which, in turn, causes an increased STJ pronation moment and active pronation of the STJ during late midstance.[48]

The neuromotor effect 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 they 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.[48]

Another important point regarding the neuromotor effect of foot orthoses is in the positive effects of them on balance. Over the past 20+ years, research on the effects of foot orthoses on balance has explored

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how foot orthoses may improve balance by either a biomechanical (i.e., direct mechanical) effect or a somatosensory (i.e., neuromotor) effect. There are now numerous studies which have shown that foot orthoses can have a very positive effect on standing balance.[83-88] In a recent review article on the effects of foot orthoses and shoes on balance in healthy older adults, Aboutorabi, et al. concluded that "foot orthoses can improve functional measures of stability in older adults" and that, indeed, "foot orthoses improve postural stability via a somatosensory or biomechanical effect."[89]

There are now numerous studies which have shown that foot orthoses can have a very positive effect on standing balance.[83-88]

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, podiatrists will possess the knowledge to use custom foot orthoses to provide their patients with an exceedingly powerful conservative treatment modality to help heal 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 in order to reduce the abnormal stresses acting on or within the injured structural components of the foot and lower extremity that are causing the pain and disability in the patient.[90,91]

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 orthoses to greatly improve the therapeutic success of foot orthosis therapy. The Tissue Stress Approach directs orthosis treatment toward reducing stress on injured tissues, rather than directing orthosis treatment toward "preventing compensations" for rearfoot and forefoot deformities, as had been previously taught in podiatry schools over the past half-century.[11,43,90,91]

The author's 34 years of clinical experience in making over 20,000 pairs of orthoses for injured patients has shown that not only is healing from injury accelerated by judiciously using the Tissue Stress Approach to orthosis therapy, but other injuries may also be prevented in the future. The tissue stress approach will lead to 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.

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 reduce abnormally high plantar pressures, reduce abnormal external and internal tissue stresses, and may reduce excessive or abnormal joint motions in the joints of the foot and lower extremity.

However, when foot orthoses are not prescribed properly, they may also 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 overriding 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**

Much more research is needed to add further clarity to the subject of how foot orthoses biomechanically and neurologically produce their beneficial therapeutic effects.

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SEE ANSWER SHEET ON PAGE 129.

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.

8) Which of the following are true about external forces and internal forces acting on

Continued on page 128

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 129.

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EXAM #8/19
How Do Foot Orthoses Work?
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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**

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

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6) What overall grade would you assign this lesson?

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