There has been little change to the theories on how the foot functions that were proposed by Root et al in 1977. However, since the time that those theories were proposed, there have been improvements in the tools that can be used to measure the movements and stresses of the foot. The concepts of the normal foot as proposed by Root et al have been questioned in some recent literature. Payne has reviewed some of the questions regarding the current state of the theories presented by Root et al. This article will propose an approach different from that of Root et al to understanding how the foot functions.

Perhaps one of the reasons that there has been little application of the new tools to the questions of podiatric biomechanics is that there has been little instruction in, or understanding of, the measurements made with the more recently developed tools. A goal of this article is to explain one of these tools: the measurement of the center of pressure. Some possible clinical uses of the information derived from this measurement will be explored.

Many different applications of center-of-pressure measurements have been proposed in the literature. However, some of these articles have suggested uses for this measurement before they have explained the meaning of center of pressure into their discussions. It is difficult to evaluate the assumptions made in some of these articles without this explanation. Center of pressure has been used in, and integrated well into, the explanation of bipedal balance.

This article will first explain center of pressure and then discuss how the location of the center of pressure might be used to infer the relative amount of mechanical stress on specific anatomical structures. The amount of mechanical stress on a structure may be related to pathology in that structure. Another goal of this article is to propose a model to explain how the location of the center of pressure in relation to the location of the subtalar joint axis can be used to understand and treat various pathologies of the foot.

Any new model that is proposed should explain the successes of past models as well as add new insights. Root et al proposed a link between subtalar joint pronation and hallux abducto valgus. Their model describes how pronation of the subtalar joint causes an increase in hypermobility of the first ray. One difficulty with this model is that hypermobility is too loosely defined to measure. (What is the dividing line between normal mobility and hypermobility?) If a parameter cannot be measured, it is difficult to perform a study that would either verify or refute the theory based on that parameter. However, this difficulty in measurement does not mean that there is not...
a link between subtalar joint pronation and hallux abducto valgus. This article will examine a different theoretical link between subtalar joint pronation and various pathologies of the foot. Specifically, this article will propose that the measured location of center of pressure, relative to the subtalar joint axis, can be used to help predict and understand pathology within the foot. Before this link can be explored, some basic principles must be understood.

**Explanation of Principles**

**The Effect of Ground-Reactive Force on the Foot and Subtalar Joint**

Ground-reactive force may or may not create a moment (torque) about the subtalar joint axis. Subtalar joint motion is a rotation and not a linear motion; therefore, a moment, rather than a force, is needed to cause the subtalar joint to move. In order to calculate the moment around the subtalar joint, one must know the magnitude of the force, its location, and the distance from the line of action of that force to the subtalar joint axis.\(^\text{14}\) In order to understand this, the definition of center of pressure and the line of action of a force must be understood. Once these concepts are understood, the effect of center-of-pressure location relative to a joint axis can be used to learn the moment from ground-reactive force acting on the subtalar joint. Once the moment is known, the concept of rotational equilibrium can be used to determine the relative amount of stress in certain anatomical structures.

**Center of Pressure**

When the foot is in the stance position, every point of the foot that is in contact with the ground will have some force or pressure applied to it. (Force equals pressure divided by area.) All of these forces from different locations can be averaged to arrive at a single force that is equal to the sum of the magnitudes of all of the smaller forces acting at a single point. This point is called the center of pressure.

The center of pressure is defined as the point at which there is no moment from all of the applied forces.\(^\text{14}\) This concept was demonstrated in an experiment by Hicks\(^\text{15}\) in which a cadaveric foot was placed on a flat board and the tibia was loaded. On the other side of the board, a pin was used to resist the load on the tibia. Hicks moved the pin until the board did not rotate from the position where the board was parallel to the ground. When the forces from the pin and the foot are aligned, there will be no moment acting on the board and it will not rotate (Fig. 1A). In this situation, the pin is located at the center of pressure of the foot. If the pin were moved from this position, a force couple would be created and the board and foot would rotate. For example, if the pin is placed posterior to the ankle joint, the ankle joint will plantarflex unless the moment is resisted by tension in a muscle (Fig. 1B).

The overall center of pressure is calculated by first finding the center of pressure in one direction (eg, the anteroposterior or x direction) and then finding the center of pressure in the other direction (mediolateral or y direction). Each location of pres-

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**Figure 1.** A, Representation of the experiment by Hicks.\(^\text{15}\) The downward arrow represents the location of the center of pressure from the foot applied to the board. The upward arrow represents the location of a pin that resists the downward force applied to the top of the tibia. The forces are directly aligned and the board will not rotate. B, The force from the pin applied to the board is posterior to the force from the foot applied to the board. In this situation, a force couple is created and the board and the foot will rotate in the direction of plantarflexion.
pressure is assigned an (x,y) coordinate. For each location of pressure, the pressure is multiplied by its x direction coordinate to create a pressure times distance value. These values are summed and the result is divided by the sum of the pressure values to yield the center of pressure in the x direction. This calculation is then repeated for the y direction to yield the center of pressure in the y direction. An example of this calculation follows. In Figure 2 there are five units of pressure at the point (1,3), three units of pressure at the point (2,1), and two units of pressure at the point (3,3). Summing the products of the pressures and distances in the x direction gives \[5 \times (1) + (3 \times 2) + (2 \times 3)\] = 17. Summing the pressures for the three points gives \(5 + 3 + 2 = 10\). Dividing the sum of the products of the pressures and distances by the sum of the pressures gives \(17/10 = 1.7\) for the x direction. For the y direction, the sum of the products of the pressures and distances is equal to \[5 \times 3 + (3 \times 1) + (2 \times 3)\] = 24. The sum of the pressures for the three points in the y direction is \(5 + 3 + 2 = 10\). The center of pressure in the y direction is \(24/10 = 2.4\). Thus the center of pressure in Figure 2 is the point (1.7, 2.4). This demonstrates how pressures from multiple locations can be averaged to obtain a single point.

A brief description of how pressure can be used to calculate a point that represents the total of ground-reactive force is warranted. Pressure-distribution measurement is done with an array of sensors. Essentially, many small sensors are placed side by side to measure the distribution of pressure over a wider area. If these sensors are calibrated with a known pressure, then the output from each sensor should be reported as a pressure. The force on each sensor can then be calculated by multiplying this pressure by the area of the individual sensor. Thus pressure and force are intimately related. The formula used for obtaining center of pressure could also use force at individual locations because of the arrangement of the equation. Pressure is in both the numerator and the denominator of the equation, so it is canceled out of the result; therefore, the result of the equation is a unit of distance. The result would be the same regardless of whether force or pressure were used in the equation.

During gait, the location of the center of pressure will change over time. For example, in the first part of the step, when only the heel is in contact with the ground, the center of pressure will be in the heel. Later in the gait cycle, after heel-off, the center of pressure will be under the forefoot. If the center of pressure is measured over time and then plotted over a picture of the foot, a path of the center of pressure will be produced (Fig. 3).

Sometimes there is confusion between center of pressure and the location of peak pressure. For example, there are an infinite number of situations in which the center of pressure may be located beneath the second metatarsal head. One possible situation is when the center of pressure from the rest of the foot averages to the location of the second metatarsal head and there is no pressure on the second metatarsal head. Another situation could exist in which all of the ground-reactive force is on the second metatarsal head. In these two situations, the center of pressure is in the same location, but the actual amount of force at the location of the center of pressure varies from zero to full body weight. The center of pressure may or may not be located in an area of high pressure. Often in gait, the path of the center of pressure will be under the medial arch at a point where there is no contact with the ground. When this occurs, the pressures on the forefoot and the rearfoot have averaged to a spot that is not even in contact with the ground. Yet ground-reactive force can be considered to act at this point for the calculation of joint moments.

One advantage of using center-of-pressure calculations is that it does not matter how rigid the joints are in attempting to assess the motion caused by a number of forces. All that needs to be done is to measure the amount of pressure in all locations on the plantar surface of the foot. Once the force is applied in a particular location, the center of pressure is calculated and the variations of rigidity have already been taken into account. Figure 4 shows that equal weight is supported whether the beam is rigid or flexible, and the center of pressure is the same. Equal weight must be supported because the objects are of equal mass; therefore, the force needed to counteract the force of gravity is the same in both cases. Neither object is accelerating, so the net force on both objects is zero.

![Figure 2](image-url)  
*Figure 2. Graph with different magnitudes of force applied to three different points. The point (1.7, 2.4) is the center of pressure for the three forces. (See text for details of calculation.)*
Line of Action of Force

Three things are needed to describe a force as it relates to the foot: its location, its magnitude, and its direction. The center of pressure describes the location where the force can be considered to act. The sum of the individual forces describes the magnitude of the total of ground-reactive force. The direction of the force is described by the direction of the arrow of its vector. The line of action is a line that extends both forward and backward from a particular vector (Fig. 5). For example, in stance, the line of action of the force of gravity acting on the center of mass of the body will extend from the center of mass down toward the center of the earth. Gravity acts toward the center of mass of the object exerting the gravitational pull. The line of action of ground-reactive force extends vertically upward from its center of pressure (when the body is not accelerating in an anteroposterior or mediolateral direction). The direction of ground-reactive force may change with various activities. For example, at the start of a sprint, there is a large posterior-to-anterior component of ground-reactive force in response to the push from the muscles of the sprinter. The force from the ground pushes the sprinter in the anterior direction, and the force from the muscles pushes the earth in the posterior direction. However, in static stance, ground-reactive force is vertical because it only resisting the pull of gravity on the body and there is no horizontal acceleration.

Location of Force Relative to Axis and Moments

The importance of knowing the line of action of a force is related to its use to calculate the moment of force about a joint axis. The moment of a force is equal to the product of its magnitude and the perpendicular distance from its line of action to the axis of the joint in question. This concept can be used to further clarify center of pressure. Take the hypothetical situation shown in Figure 5A. The 300-N force on the heel has a line of action that gives it a 5-cm lever arm at the ankle joint. This creates a plantarflexion moment of 1,500 N·cm. The 100-N force on the forefoot
has a 15-cm lever arm on the ankle joint, which gives it a dorsiflexion moment of 1,500 N·cm at the ankle joint. When the moments are added, they produce zero net moment.

In Figure 5B, the vertical force from the center of pressure has no lever arm, so there is no net moment at the ankle joint in this situation. The center of pressure in the anteroposterior direction is equal to \( \frac{(300 \times 0) + (100 \times 20)}{300 + 100} = 2000/400 = 5 \text{ cm} \). The ankle axis is located at 5 cm, which means that the ankle axis is at the same location as the center of pressure. The moment, at the ankle joint, from the center of pressure is zero. This is equal to the calculation of moments from the two individual forces. The fact that the center of pressure is beneath the ankle joint is a coincidence. The center of pressure could be moved, by the contraction of muscles, and this would alter the relative amounts of force in the two locations (eg, 250 N on the heel and 150 N on the forefoot would yield a dorsiflexion moment, from the ground, acting at the ankle joint).

**Rotational Equilibrium**

The location of the center of pressure relative to the subtalar joint axis will give a moment from ground-reactive force. This moment from ground-reactive force may be only a small part of the total moment acting on the foot. The concept of rotational equilibrium can be used to calculate the existence of other moments acting on the foot about the subtalar joint.\(^{14}\)

Equilibrium is a condition in which neither the linear nor the angular velocity is changing. This occurs at constant velocity, which is when the acceleration is zero.\(^{14, 16}\) The most common condition when the acceleration is zero is when the body is at rest, or the body’s velocity is equal to zero. When an object is in equilibrium, it will have no net force or moment acting on it. This comes from Newton’s second law (net force equals mass times acceleration, or, for rotational motion, net moment equals moment of inertia times angular acceleration; when velocity is constant, acceleration equals zero). When the net force or moment equals zero, there may still be forces or moments acting, but they cancel each other out. For example, the force of gravity on the body is exactly canceled by ground-reactive force when the body is at rest.

Equilibrium can be used to assess stress within the foot. For example, when there is a pronation moment from ground-reactive force and the foot is not moving, then there must be a supination moment from some other source within the foot. The anatomical structure or structures that resist a pronation moment from the ground will be under some stress. This stress will be related to the magnitude of the moment from the ground.

**Relation of Center of Pressure to Subtalar Joint Axis**

Ground-reactive force may or may not create a moment at the subtalar joint. Classically, the effects of
ground-reactive force on the forefoot and rearfoot on the subtalar joint have been assessed independently. However, the location of the center of pressure can be used to combine the effects of the forefoot and the rearfoot in terms of what ground-reactive force will attempt to do to the subtalar joint. (The word “attempt” is used in the previous sentence because the net moment about the subtalar joint will determine where the joint moves.) There may be moments from bones, muscles, or ligaments that will be added to the moment from ground-reactive force to create the net moment for the subtalar joint. For example, the ground may be causing a pronation moment and the muscles may be causing an equal supination moment so that when the moments are combined, there is no net moment, and there is no movement, even though there is an external moment from ground-reactive force acting on the subtalar joint. In order to know the amount and direction of the moment at the subtalar joint, from ground-reactive force, the location of the subtalar joint axis and the location (center of pressure) and direction of ground-reactive force must be known. This is a three-dimensional relationship that is best viewed in the transverse plane (when the force is pointed toward the viewer) (Fig. 6). The distance can be calculated easily in three dimensions from the equation of the lines that represent the line of force and the joint axis.

Variation in Position of the Subtalar Joint Axis

There may be a wide variation in the location of the subtalar joint axis among people. Kirby introduced the idea that a foot with a more medially deviated subtalar joint axis is more likely to have a pronation moment from ground-reactive force, while a foot with a more laterally deviated axis is more likely to have a supination moment (or a smaller pronation moment) from ground-reactive force. This concept is based on the assumption that the center of pressure will be in a similar location for both types of feet. Thus a foot with a laterally deviated subtalar joint axis is more likely to have its center of pressure medial to its axis. Conversely, a foot with a medially deviated subtalar joint axis is more likely to have its center of pressure lateral to the axis. This assumption has not been proven, but is intuitive.

The following sections will attempt to describe some specific pathologies that might be caused by variations in the position of the center of pressure in relation to the subtalar joint axis. Some treatments of some of those pathologies will also be explained in terms of moments around the subtalar joint axis.

Center of Pressure Medial to the Subtalar Joint Axis

When the center of pressure is medial to the subtalar joint axis, there will be a supination moment from ground-reactive force. For equilibrium to be maintained, there must be a pronation moment from some structure within the body. When there is a supination moment from ground-reactive force and the foot is not moving, there must be a pronation moment from some other source. This source must be something other than ground-reactive force because all of the ground-reactive force is averaged into the center of pressure. One possible source is the end of the range of motion, in the direction of supination, of the subtalar joint. Of course, for this to occur, the foot would have to be in a markedly inverted position. The end of the range of motion may be caused by either the joint capsule or the ligaments that cross the subtalar joint. The calcaneal fibular ligament is an example of a structure that could create a pronation moment around the subtalar joint axis when the subtalar joint is at the end of its range of motion in the direction of supination. A structure that could cause a pronation moment at a subtalar joint position other than the end of the range of motion is the peroneus brevis muscle. There would have to be constant contraction of the muscle to prevent the subtalar joint from supinating in the presence of a supination moment from ground-reactive force. This is a good explanation of why peroneal tendinitis might occur.

Lateral Ankle Instability. An ankle sprain is a dynamic process that is the result of supination of the subtalar joint. A person may be walking and experience an unexpected amount of supination moment.
from ground-reactive force. For example, a pebble under the medial heel may cause an unexpected medial shift in the location of the center of pressure. In this case, the ground would exert a greater supination moment than expected and the foot may begin to supinate before the rest of the foot comes into contact with the ground. This scenario could occur in all types of feet; however, it is more likely to occur in a foot that has more area lateral to the subtalar joint axis (e.g., a foot with a laterally deviated subtalar joint axis).

A foot with the center of pressure medial to the subtalar joint axis will have more of a supination moment from ground-reactive force than a foot with a different relationship between the axis and the center of pressure. The variability of subtalar joint axis position could theoretically explain why some feet are more predisposed to ankle sprains than others. The larger the supination moment from ground-reactive force, the more likely the foot is to supinate and experience an ankle sprain.

**Subtalar Joint Axis Movement and Inversion Sprains.** An important factor in the occurrence of inversion sprains is the location of ground-reactive force changes relative to the subtalar joint axis as the foot supinates around the subtalar joint axis. As the foot supinates around the subtalar joint axis, the foot moves more medial to the projection of the axis onto the ground (Fig. 7). This occurs because the subtalar joint axis is determined by the shape of the articular facets of the subtalar joint. As the subtalar joint supinates, the leg and talus externally rotate; therefore, the axis of the subtalar joint also externally rotates. The point of contact between the foot and ground does not change. The axis is rotating above the point of contact between the ground and foot. The axis may rotate to a position where all of the foot-ground contact is medial to the subtalar joint axis, in which case ground-reactive force would cause a supination moment at the subtalar joint.

There are other explanations for recurrent ankle sprains, including peroneal muscle weakness or injury, increased latency of contraction of the peroneal muscles, ligamentous laxity, calcaneal inversion, and forefoot valgus. Some of these conditions can be related to moments about the subtalar joint. Peroneal muscle weakness or injury would lead to a decrease in pronation moment at a time when pronation moment is needed to prevent a sprain. Increased latency, a delay in the activation of the peroneal muscles, would allow the foot to supinate further before a pronation moment could be applied. This is critical because as the foot is supinating around the axis, the leverage of ground-reactive force to cause supination is increasing.

The success of certain treatments for lateral ankle instability can be explained by looking at the location of center of pressure relative to the subtalar joint axis. A lateral flare placed on the heel of a shoe will place the point of contact more lateral to the subtalar joint axis. The lateral flare greatly increases the probability of a pronation moment being present, from ground-reactive force, at the instant of heel contact. A lateral flare on the heel of a shoe has been shown to increase pronation velocity, which is consistent with an increased moment from ground-reactive force.

The positive effect of a forefoot valgus wedge on lateral instability can be explained as well. One effect of a valgus wedge under the forefoot might be to shift the center of pressure to a more lateral location, which would increase the pronation moment from ground-reactive force. The wedge may also increase the pronated position of the subtalar joint, which will also tend to internally rotate the leg, making the axis appear less laterally deviated.

The idea that ankle sprains are related to an individual’s subtalar joint axis position creates an interesting scenario in terms of ligamentous stability and the likelihood of inversion sprains. Chronic lateral ankle instability has been attributed to “loose ligaments.” However, the ligaments do not play an important role in limiting motion until the joint reaches the end of its normal range of motion in the direction of supination. Loose ligaments do not explain the motion that occurs before the ligaments become taut at the end of the range of motion in the direction of inversion. If the ground were to push the subtalar joint in the direction of pronation, the lateral ligaments would never become taut and would not be needed to make the subtalar joint stable. When the ground does push the subtalar joint toward inversion, the ligaments become important for stopping motion. The instability could exist because of subtalar joint axis position and supination moment from the ground that causes the supination moment before the ligaments come into play. The lax ligaments may be the result, rather than the cause, of recurrent sprains. Therefore, it makes sense that there is a correlation between lax ligaments and ankle sprains, but the lax ligaments may not necessarily be the cause of the ankle sprains. The distinction between functionally unstable and structurally unstable ankle joints has been made. The functionally unstable ankle joint is one in which no ligamentous laxity is found, but the patient complains of recurring “twists of the ankle.” This functional ankle instability could be explained by a high supination moment from the ground (center of pressure medial to axis) and/or a low pro-
nation moment from some other source (increased peroneal muscle latency, decreased proprioception, or peroneal muscle weakness).

**Laterally Deviated Axis Predictions.** A foot with its center of pressure medial to the subtalar joint axis will tend to have characteristics different from those of a foot with a different relationship. Following are some theoretical predictions of how a foot like this will behave. The technique advocated by Kirby\(^8\) of palpating the location of the subtalar joint axis entails placing the subtalar joint in the position it is in during stance and then pushing dorsally in an attempt to cause motion of the subtalar joint. In the axis palpation technique in a foot with a laterally deviated subtalar joint axis, pressure on the medial heel will supinate the subtalar joint much more easily than it would in a foot with an average axis position. While performing this test, the author has noted that some patients reflexively contract their peroneus brevis muscle in response to a force on the heel that causes an inversion moment. This reflexive contraction makes determination of the location of the subtalar joint axis more difficult, because it prevents the motion that is expected. In stance, this foot will exhibit

**Figure 7.** A, Wooden model of the foot with hinges representing the subtalar and ankle joints. B, The subtalar joint axis is pointed at the viewer. An upward force on the lateral forefoot will cause a pronation moment. C, The leg has externally rotated and the foot has inverted to a point where an upward force on the lateral forefoot will cause a supination moment. (See text for details.)
joint will supinate maximally (Kevin Kirby, DPM, personal communication, 1994).

**Center of Pressure Beneath the Subtalar Joint Axis**

When the center of pressure is directly beneath the subtalar joint axis, there will be no moment from ground-reactive force. The forces from the ground will balance around the subtalar joint axis. In this situation, the moment from ground-reactive force on the medial side of the subtalar joint axis exactly balances the moment from the lateral side of the subtalar joint axis. When this happens in a foot, no internal stress is needed to counteract the effects of ground-reactive force around the subtalar joint axis. There may be stresses about other joints.

In contrast to the foot with the center of pressure medial to the subtalar joint axis, this foot can stand without any muscle contraction. When the center of pressure is directly beneath the subtalar joint axis, equilibrium around the subtalar joint could theoretically be achieved in any position of the subtalar joint. However, for any given foot, there would be only one position of equilibrium of the subtalar joint. In a foot with the center of pressure directly underneath the subtalar joint and a position that is more laterally deviated, how equilibrium is achieved must be examined. With the more laterally deviated subtalar joint axis, the distances from the points lateral to the axis will be smaller than in a foot with an average axis. Therefore, for the moments from the forces on both sides of the axis to be equal, the forces must be relatively higher lateral to the axis because the distance is smaller. The author has observed feet in stance that do not have muscles contracting and have high forces under the lateral forefoot (measured by placing fingers under the lateral forefoot) and that have subtalar joint range of motion available in the direction of eversion. A foot in this position is contrasted with the uncompensated, or partly compensated, forefoot or rearfoot varus foot. The partly compensated varus foot will have high lateral forefoot forces, but will have no range of motion available at the subtalar joint in the direction of eversion. The varus foot will be discussed in the next section.

**Center of Pressure Lateral to the Subtalar Joint Axis**

When the center of pressure is lateral to the subtalar joint axis, ground-reactive force will cause a pronation moment about the subtalar joint axis. For equilibrium to be maintained, there must be an anatomical structure or structures that are supplying a supination moment about the subtalar joint. When the pronation moment from ground-reactive force is higher, the stress in those structures will be higher and pain in those structures is more likely to occur.

**Structures That Create a Supination Moment.**

There are many structures that could resist a pronation moment from the ground. The floor of the sinus tarsi, the medial slip of the plantar fascia, and muscles will be discussed. A single structure or multiple structures may contribute to resisting a pronation moment from the ground.

**Floor of the Sinus Tarsi.** The subtalar joint reaches the end of its range of motion in the direction of pronation when the lateral process of the talus slides anteriorly and inferiorly to the point where it touches the floor of the sinus tarsi of the calcaneus. When this occurs, there is bone-on-bone contact and there can be no further motion about the subtalar joint axis in the direction of pronation. Pain in the sinus tarsi could occur when the floor of the sinus tarsi is the only structure resisting a pronation moment from the ground. The floor of the sinus tarsi is a very short distance from the subtalar joint axis. If the center of pressure was twice as far from the subtalar joint axis as the floor of the sinus tarsi, to maintain equilibrium the force in the floor of the sinus tarsi would have to be two times body weight (ie, if the floor of the sinus tarsi were the only source of supination moment).

Understanding the compressive forces in the floor of the sinus tarsi is important for estimating the amount of force that a silicone plug from a subtalar arthroereisis procedure would have to resist to hold the subtalar joint in a more inverted position. This is especially important because the subtalar arthroereisis changes the location of the end of the range of motion of the subtalar joint, in the direction of pronation. This places the foot in a more inverted position, which is more likely to place the center of pressure more lateral to the subtalar joint axis, thus creating a higher pronation moment from the ground, which must be resisted by a supination moment from the floor of the sinus tarsi (or the silicone plug from the subtalar arthroereisis). The subtalar arthroereisis may create a partially compensated rearfoot varus in which the maximally pronated position of the subtalar joint will be inverted. When the foot is in an inverted position, the center of pressure is much more likely to be more lateral to the subtalar joint axis, which will create a higher pronation moment from the ground.

**Medial Slip of the Plantar Fascia.** Most of the
time, activation of the windlass mechanism will cause supination of the subtalar joint.\textsuperscript{28, 29} There are some rare exceptions to this.\textsuperscript{30} Winding up of the windlass mechanism causes the subtalar joint to supinate. The windlass mechanism can work in reverse: as the subtalar joint pronates and the arch lowers, the fascia becomes tight.\textsuperscript{29} When this happens, the medial slip of the fascia is creating a supination moment about the subtalar joint. The greater the tension in the fascia, for any given foot, the greater the supination moment from the fascia. This supination moment about the subtalar joint from the fascia could counteract a pronation moment from ground-reactive force.

**Muscles.** Any muscle that could cause a supination moment could counteract the pronation moment from the ground when the center of pressure is lateral to the subtalar joint. This is explained well in the article by Kirby\textsuperscript{16} on rotational equilibrium. The muscles that can do this—ranked by length of lever arm, from longest to shortest, and thus by ability to create an inversion moment, from greatest to least—are the tibialis posterior, flexor digitorum longus, and tibialis anterior.\textsuperscript{13} The longer the lever arm of the muscle, the less force is required of the muscle belly to resist the pronation moment from the ground.

Confusion may arise regarding cause and effect of the location of the center of pressure and muscle activation. Contraction of the posterior tibial muscle will cause a lateral shift in the center of pressure.\textsuperscript{15, 16} If a lateral location of the center of pressure is observed (or high forces on the lateral midfoot and forefoot), this may be caused either by a muscle that creates a supination moment or by the end of the range of motion of the subtalar joint, as seen with the partly compensated rearfoot or forefoot varus foot.

Posterior tibial muscle dysfunction is a pathology that is theoretically related to the center of pressure’s being lateral to the subtalar joint axis. When there is a medially deviated subtalar joint axis, the posterior tibial muscle may have a smaller lever arm, which causes the supination moment,\textsuperscript{16} and the center of pressure may have a greater lever arm, which causes pronation. If this were to occur, the force in the posterior tibial muscle and tendon would have to be much greater to cause the same moment or motion as compared with a foot with an average subtalar joint axis location. Excessive force in the posterior tibial tendon has been described as a cause of posterior tibial muscle dysfunction.\textsuperscript{32}

**Redundancy.** In mechanical engineering, redundancy occurs when more than one structure is responsible for creating a force or a moment. When there is more than one source of supination moment resisting the pronation moment from the ground, it is difficult to determine the relative load on a single structure. For example, if the posterior tibial muscle were the only source of supination moment that was opposing a pronation moment from the ground, the moment from the muscle would equal the moment from ground-reactive force. However, if another muscle that creates a supination moment were contracting at the same time, it would be impossible to determine, from external measurement, what percentage of the supination moment was coming from which muscle. Center of pressure is an external measurement. The concept of redundancy also applies to structures other than muscles. For example, tension in the medial slip of the plantar fascia and activation of a muscle that creates a supination moment could together create a supination moment that would counteract a pronation moment from ground-reactive force.

**Medially Deviated Axis and Force on the First Metatarsal Head.** It has been implied that ground-reactive force on the first metatarsal head will stop pronation.\textsuperscript{1} However, when the subtalar joint axis is medial to the head of the first metatarsal, ground-reactive force on the first metatarsal head will cause a pronation moment at the subtalar joint. When unopposed, this pronation moment will cause further eversion of the subtalar joint. Further eversion of the rearfoot, if range of motion is available, will tend to increase force on the first metatarsal head. Pronation must be stopped by a supination moment from some anatomical structure, because when the center of pressure is lateral to the subtalar joint there will be a pronation moment from the ground that must be opposed by a supination moment from somewhere. When there is significant eversion available from the subtalar joint and a more medially deviated position of the subtalar joint axis, significant stress on the medial slip of the plantar fascia or muscles that create a supination moment is much more likely, because these are the structures that resist a pronation moment from the ground when the subtalar joint is not at the end of its range of motion.

The foot with a more medially deviated subtalar joint axis would be more likely to have a high pronation moment from the ground. Therefore, the structures that resist the pronation moment from the ground are more likely to have excessive stress and pathology. The floor of the sinus tarsi and the posterior tibial muscle have been described as applying a supination moment about the subtalar joint.\textsuperscript{16} The medial slip of the plantar fascia has been described as applying a supination moment about the subtalar joint. High tension in the fascia has been theoretically linked to heel spur syndrome, hallux limitus, and hallux abducto valgus.\textsuperscript{33}
Treatment. Sinus tarsi syndrome, plantar fasciitis, heel spurs, hallux limitus, hallux valgus, and posterior tibial muscle and tendon dysfunction may be related to the foot’s having a high pronation moment. All of the structures in these pathologies may be placed under more stress when there is a large pronation moment from the ground. This may explain why these pathologies may improve when there is more supination of the subtalar joint in gait. This could also explain the potential for more successful treatment of these conditions with orthotic modifications that increase the supination moment.34 It should be obvious why these devices are contraindicated in the treatment of peroneal tendinitis. Further research is needed to determine whether these devices achieve their effect by shifting the location of the center of pressure.

Discussion

This article attempts to 1) explain the commonly used engineering measurement of center of pressure and 2) explain how the use of center of pressure can be extended to formulate a model by which various pathologies of the foot can be explained. The first part of this section will look at the use of center of pressure in the literature. The second part will compare this model of the foot with other models of the foot.

There are two broad categories of the use of center of pressure in the literature: balance control and evaluation of foot function. Winter et al8 describe how an individual can use various muscle strategies to alter the location of center of pressure relative to the center of mass to maintain balance. In their article, the moments acting on the whole body and about specific joints are taken into account in the explanation of how a person can maintain an upright posture.

A method to evaluate foot and orthosis function has been proposed by Scherer and Sobiesk.7 They propose a center-of-pressure index that is the ratio of the area of the foot lateral to the center-of-pressure line, to the area of the foot medial to the center-of-pressure line. The authors state that a foot with a more lateral center-of-pressure path during gait is a more stable foot. They do not state how they arrived at this conclusion. The model proposed in this article could explain a more lateral path of center of pressure for two different reasons. The partly compensated forefoot or rearfoot varus foot would show a more lateral center-of-pressure path. Also, a foot with increased muscle activity, which creates a supination moment, could create a more lateral position of the center-of-pressure path. Any measure of foot stability that uses center of pressure would have to reconcile the many different possible sources of moment that contribute to the location of center of pressure. The variability of the center-of-pressure index has been found to be high enough to call into question its use as an accurate predictor of foot function.35

Song et al10 propose a measurement called the center-of-pressure excursion index. This measurement appears to be very similar in concept to the center-of-pressure index proposed by Scherer and Sobiesk.7 Although Song et al do not give the formula for calculation of their center-of-pressure excursion index, they do describe it as “the lateral displacement of the center of pressure curve from the reference line.” They found that the center-of-pressure excursion index, by itself, was not a good method to use to differentiate a planus foot type from a rectus foot type. One possible reason for this is that lateral excursion of the center-of-pressure path could be explained by either the end of the range of motion or muscle contraction, as was mentioned in the previous paragraph.

Another approach to the use of the center of pressure is the sagittal plane facilitation theory proposed by Payne and Dananberg.9 This theory proposes that there are changes in the path of the center of pressure in the presence of functional hallux limitus. Treatment is directed at observing the center of pressure and making alterations in an orthosis so that the path of the center of pressure is changed. This approach makes some observations about the location and the velocity of the path of the center of pressure and attempts to correlate them with some physical findings. These findings include whole-body changes in gait in the presence of hallux limitus.36,37 However, the definition of center of pressure is not incorporated into this theory, which creates some difficulties in terms of whether the observations seen are a cause or an effect. One of the components of the sagittal plane theory is the concept of sagittal plane blockade. A functional hallux limitus is theorized to make the foot into a longer lever that makes normal progression of the body over the foot more difficult. If this were a direct mechanical effect, one would expect the center of pressure, at a time near heel-off in gait, to be located further distally than on a foot without hallux limitus. If a person with hallux limitus were to walk in a manner to avoid the longer lever arm (eg, extensor substitution), the person might have a center of pressure, at a time near heel-off in gait, less distal than a person without hallux limitus. At the time of this writing there was no published description of exactly what measures of the center-of-pressure progression are used to make the orthotic alterations, so it is difficult to compare the definition.
of center of pressure with the theoretical predictions of the sagittal plane facilitation theory. The sagittal plane facilitation model of foot function is a promising area of future research because pathology is related to objective measures and these measures are altered with treatment.

The sagittal plane facilitation approach is a model that attempts to use center of pressure to explain the success of orthotic treatment. Of course, not all models of foot function have to incorporate the location of center of pressure into their framework. Root et al proposed a model in which an idealized normal foot is created and positional variations from that normal foot are identified and treated. Pathology is theorized to be related to the fact that the foot is not in the position of the idealized normal foot. Although there is disagreement in the literature on the effectiveness of this approach, it has become accepted in the podiatric community. A disadvantage of this approach is that it examines the position of the joints of the foot instead of the stress on anatomical structures. Another disadvantage of this approach is that the effects of ground-reactive force on the forefoot and the rearfoot are separated. For example, there could be a pronation effect on the rearfoot and a supination effect from a forefoot deformity, with no way of reconciling the two effects. This is not a problem when the location of the center of pressure relative to the subtalar joint axis is known.

The approach of looking at the center of pressure relative to the subtalar joint axis creates an additional model of the foot that does not have some of the disadvantages of the normal foot approach. The ability to quantify the pronation moment also creates an area for future research. This model predicts that those patients with a high pronation moment from the ground are more likely to have certain pathologies (eg, hallux abducto valgus) and less likely to have other pathologies (eg, peroneal tendinitis). Methods to measure the moment from ground-reactive force in gait have already been reported. Various mechanical treatments can be evaluated for their change in location of center of pressure and, hence, the change in moment from ground-reactive force. More directly, the change in location of ground-reactive force may be measured, and this change can be compared with improvement in symptoms. In contrast, the theories of Root et al use poorly defined and difficult-to-measure terms such as “hypermobility” and “stability,” making it difficult to perform research. In addition, there is debate on whether the measurements used in the approach proposed by Root et al are reproducible.

One of the major advantages of using the location of center of pressure and axis location to explain foot function is that it offers a direct correlation between stress on a structure and the existence of a particular pathology. Treatment is then directed at reducing that stress. Even though it is possible to calculate the moment about the subtalar joint during gait, knowledge of the value of the moment is not necessary for effective treatment. With proper diagnosis of the anatomical structure involved and knowledge of how stress is placed on that structure, the physician can use a model to decide in which direction to attempt to move the center of pressure. For example, posterior tibial tendinitis is theoretically caused by a high pronation moment from the ground, and treatment would involve increasing the supination moment from ground-reactive force. A method for changing the moment from ground-reactive force has already been proposed. In addition, when the cause of pathology is known, the treatment can be directed at pushing the foot in a certain direction. In the example of peroneal tendinitis, the foot is pushed in the direction of pronation. The practitioner can then evaluate the effectiveness of the treatment and make the decision to increase or decrease the change in pronation moment. Using this approach will also give the practitioner guidelines as to what to look for if the treatment goes too far. With peroneal tendinitis, for example, too much added pronation moment could cause sinus tarsi pain.

In contrast, the theories proposed by Root et al imply that the foot’s not being in its normal neutral position will cause pathology. Treatment under the Root et al model would attempt to place this foot in neutral position and balance any forefoot-to-rearfoot deformity that exists. If the treatment is unsuccessful once this basic formula has been followed, there is little direction given to the practitioner on what to attempt next.

This article has described the use of center of pressure in the static stance situation to attempt to predict pathology. Moments from ground-reactive force can be calculated in the dynamic situation of gait as well. This is done with inverse dynamics. In the static situation, the net force is zero and acceleration is zero. In the dynamic situation, the acceleration is measured and known masses, moments, and forces are used to calculate unknown moments and forces. Therefore, the same concepts found in the static situation can be applied to the dynamic situation.

There are some difficulties in using the center of pressure relative to the subtalar joint axis as a model for treating foot pathologies. The problem of redundancy makes it difficult to predict which structure, if any, will be injured. There are many structures in the
foot capable of resisting a pronation moment from the ground. The stress from a high pronation moment could be shared evenly by many structures, with no single structure being damaged. Therefore, a high pronation moment from ground-reactive force would not necessarily result in pathology.

Another difficulty with this model is related to the direct measurement of center of pressure. It is difficult to know if the location of center of pressure is caused by passive structures or active muscle contraction. The variability in muscle contraction across steps may make it difficult to know which structure or structures are resisting a moment from ground-reactive force. However, if an anatomical structure is painful, perhaps it can be assumed that it is receiving too much stress. If research is performed using this model, muscle activity must be closely monitored.

Conclusion

Commonly used engineering principles may be helpful in understanding pathology of the foot. This article has described the measurement and potential usefulness of the location of the center of pressure relative to joint axes of the foot. This article has also proposed a theoretical framework from which the etiology and treatment of various pediatric pathologies may be explained. The location of ground-reactive force relative to the subtalar joint axis will determine the moment at the subtalar joint from ground-reactive force. The concept of rotational equilibrium may be used to infer the presence of moments from anatomical structures within the foot. These moments may be related to mechanical stress on anatomical structures, and the stress may be related to pain in those structures. Future research is needed on how the location of the center of pressure can be changed with treatment and how that change results in alteration of symptoms.

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