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Foot Posture Biomechanics and MASS Theory

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Differences between single axis and postural models of foot biomechanics are explored. Subtalar joint function is discussed and a new model explaining midfoot locking is proposed. The posture of the foot is divided into zones of postural collapse. The new postural model suggests that the foot's posture controls its function and we should begin controlling the foot's posture before postural collapse occurs. Maximal Arch Supination Stabilization (MASS) posture is proposed as the geometry of a composite leaf spring that applies a calibrated, more evenly distributed, force per unit area opposing the postural collapse that occurs as the foot is intermittently compressed during ambulation. One calibration method is explained.

Key words: biomechanics, posture, MASS theory

Single Axis vs. Postural Biomechanics

The popular school of thought in foot biomechanics is a single axis approach. Merton Root was attempting to find something he could measure that would correlate to and predict deformity [1]. He discovered that by placing the patient prone while holding the off weight bearing foot in a palpated, "neutral" position, it was observed that most heels were inverted; rearfoot varus. He noticed both rearfoot and forefoot varus did correlate well to observations of deformities, lesions, and many lower extremity pathologies. Root recommended taking 17 measurements called the Static Biomechanical Exam [2]. Treatment was aimed at correcting what was viewed as a frontal plane deformity with frontal plane correction of the rearfoot and forefoot, called posts, designed to encourage the foot into a more neutral rotational position around the subtalar joint (STJ) axis. Excellent success was attained in most cases with the reduction of symptoms that gained this model of foot biomechanics broad acceptance.

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At this writing, this model is still the backbone of the biomechanics curriculum of all colleges of podiatric medicine in the United States. Merton Root, John Weed, and Bill Orien [2] did a thorough analysis of the motions that occur in the foot, analyzed muscle firing patterns, and did a magnificent job analyzing many of the most common, and therefore important, biomechanical foot deformities. Neutral position, which Root defined as "neither pronated nor supinated", is simply a rotational position around a singular axis; the subtalar joint axis. Pronation and supination are defined in both the open and closed chains as rotations around this singular axis. The extreme of single axis theory is to imagine that the foot only has one axis and consider the foot as just two rigid bodies teetering around this singular axis. This model concerns itself with the distribution of kinetic forces and their perpendicular distance to this one axis. This describes the Subtalar Axis Location and Rotational Equilibrium (SALRE) theory of Kevin Kirby, DPM [3].

The small amount of STJ rotation is where Merton Root and Kevin Kirby concentrated their attention [4]. According to Root's own measurements the total range of STJ rotation in ideal gait is only six degrees (+2 to -4). Pierrynowski, showed that palpation accuracy for "neutral" position with experienced practitioners is +/- 3 degree [5]. Meaning the best clinicians can find any position within the ideal range of motion of rotation around the STJ axis and call it "neutral".

Craig Payne took this one step farther and studied the frontal plane rearfoot to forefoot variability of off weight bearing STJ neutral casting and found that new students, experienced doctors, and the peer-selected best caster all had the same frontal plane variation forefoot to rearfoot of 10 to 12 degrees within each group and just over 16 degrees between groups [6]. This frontal plane twist is the major determinant of arch height and, therefore, foot posture. In a personal meeting with Dr. Payne, he said that they used his foot for all tests [7]. Subsequent examination of his foot revealed a fairly rigid forefoot in the frontal plane. Sixteen degrees may have been his entire range of motion, and they found it all.

If any singular axis is to be chosen to describe foot biomechanics, the subtalar axis may be a particularly poor choice. The reasoning behind this, is in physics, when a force is applied onto one side of an axis it causes rotation in one direction, as it moves to the other side of the axis rotation occurs in the opposite direction. When the force passes directly through the axis, no rotational movement occurs. The ground reactive force enters the foot ideally on the plantar posterior lateral aspect of the heel. The STJ axis exits the foot at the same point; the momentum down the leg similarly passes its force vector down the center of the dome of the talus thereby intersecting the STJ axis. The STJ axis is placed in an orientation that passes through the major forces entering the foot at heel contact, other than the force of friction which is horizontal and causes the forward roll of the calcaneus.

No singular axis can even begin to describe the motion that occurs during ambulation or simply the elevation and collapse of the arches of the foot. The foot has 26 bones and 35 joints, all of which move in some way. Some of these joints are involved in rotation, and other joints simply slide in one plane.

Royal Whitman realized that the foot weakened its structure as its posture collapsed; calling the condition "weak foot" [8]. He may have been the first to have actually made the observation that foot posture controls its function.

Root et al, called Royal Whitman's observation the phenomena of midtarsal locking and unlocking and attributed it to Elftman's theory, that the talonavicular and calcaneocuboid axis deviated as the foot supinated [9]. Thus, this decreased the range of motion and parallelism of the axes, results in increased range of motion. The talonavicular joint is an ovoid ball and socket having an infinite number of axes. Sarrafian calls it the Acetabulum Pedis (hip socket of the foot) [10]. Whatever the rotational axis of the calcaneocuboid, the talonavicular joint will always find a parallel axis.

I propose that the locking mechanism of the midfoot is multifaceted. When the talar head is directly on top to the anterior facet, sagittal plane motion between the talus and calcaneus is blocked. Thus, when the gastroc-soleus complex fires, rotation occurs at the ankle joint.

Additionally, the Wring Theory by PC Jones describes twisting or wringing the foot into a more closed packed position; nesting the midfoot bones into each other [11]. Such a twisting would put more force on the first metatarsal head at toe off, per Root [1]. In a supinated posture the anterior facet of the STJ levels allowing transverse plane rotation of the talar head which carries with it the medial column of the foot which rides over the lateral column further restricting midfoot dorsiflexion.

Measurements taken of the geometry of the three facets on over 200 calcanei in The Terry Collection at the Smithsonian Institute yielded one consistent observation: when the anterior facet of the STJ is level in the frontal plane, the calcaneus is inverted [12]. Inversion occurs ideally at heel strike. This occurs at or near the end range of motion in subtalar supination. The talocalcaneal motion, which is a posterior and slightly lateral slide along the cone-shaped posterior facet, is accompanied by a small amount of rotation around the STJ axis. This places the head of the talus squarely on the anterior facet. This was also noted by Root [1].

The basic difference between single axis models, such as the STJ Neutral Model, and a postural model is that single axis models, by definition, ignore the rest of the foot. You can find STJ neutral in a broad range of foot postures both in the open and closed kinetic chain. Posture is simply stepping back and looking at the foot as a whole and observing the way elevation of the longitudinal arches causes bones to nest into each other in a more closed pack position. Paul Jones attributes this to a generalized spiral twisting of the forefoot on the rearfoot, The Wring Theory [11]. Sarrafian described the frontal plane forefoot to rearfoot relationship as a twisted plate. All of these models are posture based [13]. Posture is the All Axis Model.

The foot is a machine with a tented structure. The foot experiences intermittent compression between the downward force of the body and the ground, which is often in our society, a rigid surface like concrete or steel. Clinical observation confirms that over a lifetime most individuals are genetically predisposed to postural collapse. Postural collapse loosens the foot's structure and postural elevation tightens the foot. As Root [1] proposed, loosening allows for shock absorption and adaptation to the terrain and tightening prepares the foot for propulsion by creating a more rigid lever.

Postural Zones

What the STJ axis lacks in rotation, it more than makes up in translation. If we observe the foot at heel strike through midstance, we see a huge forward and plantar grade translation of the STJ axis. Southerland begins the Seven Theorems of Compensation in the Distal Human Lower Extremity with the words, "The foot hits the ground in a forward rolling motion" [14]. Jacqueline Perry describes the axis of translation as the heel rocker mechanism [15]. One of the more brilliant aspects of foot design is the round heel. Like a ball, it has an infinite number of axes all passing through the center. This allows us to hit the ground from any angle, forward or backward and apply the appropriate axis based on the direction of heel rotation with every step. Likewise, the STJ axis can translate through all of the following postural zones with each step.

Pathological Zone

Tom McPoil's Tissue Stress Theory states that when microtrauma occurs faster than a person's ability to heal, they experience a symptom [16]. During the last few degrees of postural collapse tissue stresses are highest. Microtrauma occurring in this zone of foot posture causes symptoms.

Dysfunctional Zone

As the foot goes into further elevation of its posture, there is a zone where, according to Hammel, there is no significant rotation around the STJ axis in any plane [17]. Foot orthoses that attempt to elevate posture into this zone often cause medial longitudinal arch pain as the foot repeatedly drops down to impact the orthotic. Hammel showed that from 25% to 90% of the stance phase of gait, no rotation in any plane occurs between the talus and the calcaneus. The forefoot hits the floor at 27% of the way through the stance phase. Ground reaction force applied to the forefoot displaces it superiorly in relation to the rearfoot. The most significant postural collapse occurs at this time. Subtalar rotation in the transverse and sagittal planes occurs only from heel strike to 24% of stance. Therefore, subtalar rotation and postural collapse are independent events occurring at different times in the gait cycle. Early and excessive STJ rotation does, however, move the head of the talus off of the anterior facet loosening the foot's structure, and preparing the foot for postural collapse. Subtalar pronation is not synonymous with postural collapse, but it is a predicating factor. Subtalar supination is not synonymous with postural elevation but is highly beneficial for efficient propulsion. Pierrynowski and Trotter showed that elevation of the foot's posture made a significant improvement in the Biomechanical Efficiency Quotient [18].

Functional Zone

As foot posture elevates beyond the Dysfunctional Zone the anterior facet of the STJ approaches level in the transverse plane. This allows subtalar rotation to occur. This is where the talar head slides posterior and rotates its six degrees around the STJ axis. The closer the anterior facet is to level, the easier the subtalar rotation occurs and the rearfoot locks in the sagittal plane facilitating efficient propulsion.

Supination Instability Zone

Beyond the Functional Zone, there is a zone that is not always present, where the foot can be put into so much supination that it becomes laterally unstable. As the downward force of the human body moves lateral to the foot, the propensity of inversion ankle sprain will increase due to a rotational moment created in that direction.

Composite Leaf Spring

Since the downward and deforming force of intermittent compression causes postural collapse, a corrective force would have to be applied in the opposite direction if functional change is desired. This is where a foot orthotic device comes in. A foot orthotic is a very simple machine. It is a composite leaf spring. There are two ways that such a leaf spring can be applied to the human foot.

Traditional orthotics based on the single axis models tend to be rather low in posture. The cast is taken in a partially pronated position and then the arch is further lowered to varying degrees to make the orthotic tolerable. Filling in, or lowering the arch of the orthotic, is often called "cast correction" even though it divorces the geometry of the foot from the geometry of the orthoses and allows for greater postural collapse before the orthotic is contacted by the arch. Dysfunctional Zone postures are lowered to pathologic zone postures by arch fill. As the foot reaches the end of its postural range of motion, ligaments are tightening up and the velocity of final impact is slowing down. At this point the orthotic contacts the foot in the arch and the soft tissue compression dampen the final impact. The Tissue Stress Model explains that symptoms are caused when microtrauma occurs faster than a person's ability to heal [16]. Repetitive over stressing of the soft tissues can lead to bony malalignments that we refer to as foot deformities; hallux abducto valgus or hammertoes. Symptoms become less evident when the amplitude of each tissue stressing event is decreased by soft tissue compression. This dampening can mask symptoms without making a significant functional change in the gait cycle. This explains an important contradiction. These low, flat, smooth, invented, generic-shaped orthoses with their various tilts, skives, grooves, lumps, and bumps are simply herding the terminal tissue stresses around the bottom of the foot to mask symptoms with no appreciable change in kinematics. Kirby et al, refers to these infinitesimal changes in kinematics that are so small as to be clinically meaningless [19]. He reports a statistically significant change in the angle of gait of less than 1.5 degrees, which is visually imperceptible.

This strategy is completely incapable of addressing posture because the foot is near its relaxed calcaneal stance posture when the foot's medial longitudinal arch hits the orthotic. A corrective force applied after the motion has occurred can only mitigate the damage caused by the impact. The orthotics are being used much like a car bumper. Low velocity impacts cause little or no damage to the car because the bumper dampens the impact.

A different, and in this author's opinion, better way to control the postural collapse of the foot would be to apply the corrective force throughout the entire gait cycle. Simply choose a posture of the foot that approximates the beginning of the postural range of motion. The spring flexes and limits the motion while continuously encouraging the foot back to its functional zone. This is analogous to applying your brake and controlling the motion instead of mitigating the effect of repetitive impact.

MASS Posture

MASS posture has several elements. First, it is the highest posture that the foot can attain at midstance, placing the foot in adequate supination to reach or approximate a level anterior facet of the STJ, putting it squarely within the functional zone. The idea is simple. If you want to control a motion, start at the beginning of that motion.

The foot poses a special problem. The soft tissues between the orthotic and the bones compress unevenly. Therefore, an essential element of capturing the foot in this elevated posture is that the soft tissues must be evenly compressed as they will be during use. There are many ways to achieve this.

A MASS Posture composite leaf spring applies an even distribution of force per unit of area by remaining in full contact with the foot throughout the gait cycle. The foot never has to drop down to hit the orthotic because it is already touching it, which minimizes impact and thus tissue stresses. It is the combination of full contact (redistribution of force per unit area) eliminating hot spots and the lack of repetitive impact that allow such a spring to apply a rather large corrective force while remaining comfortable to most patients. Once you have the correct geometry of the spring, it is time to adjust the spring constant.

Calibration

How much vertical force should this leaf spring apply to the foot in an evenly distributed manner? Isaac Newton supplied the answer with his third law of motion: for every action there is an equal and opposite reaction. Applying that law to this problem: the amount of force the orthotic should apply to the body is directly related to how much force the body is applying to the orthotic. What causes the downward force of the human body onto the orthotic?

Obviously, body weight is a major factor. Heavier people apply more force as measured by any household scale. The more you weigh the greater the force the orthotic must resist and, therefore, the more rigid it must be.

Foot flexibility is another factor. If the patient has Ehlers Danlos Disease, their ligaments are highly elastic and far less supportive. They contribute little to the support of the foot's posture and the orthotic must do more of the work. If the patient's ligaments are stiff, there is less range of motion and the foot generally collapses less. The ligaments provide much of the support of the foot's posture. What little postural collapse occurs is easily elevated. Foot flexibility can be measured in different ways. One way to grade foot flexibility is to rotate the forefoot around the fifth metatarsal. This is called the Gib Test or forefoot flexibility Forefoot Flexibility Test. The foot can be graded from one to five [20]

Five, being the most rigid, is less than five degrees of total rotation of the forefoot on the rearfoot. This can occur in Charcot foot, after a major trauma, or a surgical fusion. A total rotation, up and down, between five and 30 degrees, tells us the foot is on the rigid side of normal and is graded a four. Normal rotation is between 30 and 60 degrees and is graded a three. The feet that are on the flexible side of normal will rotate between 60 and 85 degrees and are graded a two. The most flexible feet, that usually collapse the most, can rotate the forefoot around the fifth metatarsal more than 85 degrees and are graded a one.

This simple grading system is not meant to be accurate. Accuracy is difficult to attain when the foot's flexibility is a moving target and can change significantly throughout a single day. Only an approximation is necessary or possible. If the clinician is unsure of whether a patient is a one or three for example, it is best to report the smaller number. That would tell the manufacturer that the foot is more flexible, and thus, make the orthotic more rigid. If the device is actually too rigid for the patient, it can easily be recalibrated down to a more flexible spring by removing material, but as material is difficult to add accurately a spring made too flexible will have to be remade thicker from scratch.

Another way to assess forefoot flexibility more directly is to compare the actual curvature of the foot in its corrective MASS posture vs relaxed calcaneal versus stance posture. These measurements are performed in the same medium to get comparable soft tissue compression in both casts. Comparing the best and worst posture will help the patient and clinician understand how they would benefit from influencing the foot's posture. This is far more objective because it shows the actual change in curvature that will occur with the posture is collapsed versus restored.

Momentum (mass times velocity) is the third factor that affects the magnitude of the downward force of the body. Running over a force plate produces more impact force than walking. Therefore, we must consider a range of forces to resist called, ADL or activities of daily living, and calibrate the orthotic to deliver an equal and opposite range. Athletes may have a different range of forces, these can be referred to as training or competing ranges, which are much higher. A power lifter, for example, may want an orthotic calibrated to resist his entire weight plus the weight he is deadlifting or squatting. That same athlete will need a different pair of orthotics for his ADL.

Munteanu showed that the more elevated the foot's posture is, the less supination resistance is measured, and the more collapsed the foot's posture is, the greater the force necessary to elevate the arch [21]. Postural elevation makes further elevation easier and postural collapse makes further postural collapse easier. Several lever arms in the foot increase and decrease to accomplish this.

Measuring the upward force delivered by the orthotic is difficult. Calibration of the orthotic can be accomplished by the application of Pascal's Law; pressure inside an enclosed container is equivalent in all directions. Place the orthotic in an enclosed container and blow up a bladder over the orthotic. As the bladder expands, it fully contacts the orthotic and begins to flex it. Flexion can then be captured digitally either via liner encoder or optics. A force curve plotting flexion against pressure gives us a slope. This slope correlates to the spring constant, which allows each orthotic to be calibrated.

Root found that in ideal gait 60% of the force applied to the ground at toe off should be under the first ray [22]. Higby measured the force distribution on the metatarsal heads at toe off [23]. What are these forces? Initially, MASS posture orthotics transferred 44% more force to the first metatarsal head at toe off than neutral position orthotics with posts. At six weeks this difference grew to 61% (p=.006) [24]. This means that when the arch is raised, the first ray not only comes down and lateral, but additionally increases its purchase.

Conclusion

Posture controls function. Postural collapse is the cause of functional impairment in the majority of foot patients and often leads to pain, pathology, and deformity. MASS posture is an aggressive approach to foot biomechanics. It attempts to restore as close to an ideal posture to the foot as each foot can tolerate with its individual anatomy. Application of a calibrated leaf spring to resist collapse of foot posture can often make early visible changes in the gait cycle. A composite leaf spring, or orthotic, must begin to resist pathologic motion or postural collapse before that motion occurs. MASS posture theory is proposed, which is a plastic leaf spring that is in full contact with the foot in the highest posture that a person can attain at mid-stance with the heel and forefoot in contact with the ground and the soft tissues evenly compressed. Such a spring calibrated to deliver an equal and opposite range of forces to those applied by the body, encourages the foot into a more functional foot posture that may reverse deformity. Form follows pathological function in the direction of disease and deformity. It stands to reason that it would similarly follow restored function in the direction of health and reversal of deformity. Further research is needed to determine the measurable effects on several diagnoses and to explore better ways to measure and document the gait changes achieved by MASS Posture.

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