Biomechanical design of functional foot orthotics: An innovative technique used as an injury prevention tool.

Claudia A. Angeli
Frazier Rehab Institute, Louisville – KY
claudia.angeli@jhhs.org

Abstract
The ankle-foot complex is considered one of the most dynamically complicated segments in the human body. The foot structure needs to be rigid to support the body and flexible enough to dynamically adjust to mechanical demands. High forces are transferred through the ankle-foot structure during contact phase, increasing the risk of injury when lower extremity joints are not aligned. Custom functional orthotics have been used widely for the correction of foot structural abnormalities. Recently functional orthotics also have been used to treat lower extremity pain syndromes caused by mechanical abnormalities.

Three-dimensional gait analysis is used to identify mechanical deficiencies of the lower extremities, but very rarely used as a tool in injury prevention. The evaluations focused on the measurement of knee, ankle and foot kinematics and kinetics. The use of biomechanical data for the design of functional orthotics will be presented. The presentation will give an overview of how design parameters for functional orthotics can reduce the risk of overuse injuries.

Biomechanical evaluations have been used as an injury prevention tool for athletes at the University of Louisville. Athletes wearing functional orthotics designed with this method have reported a reduction in lower extremity pain and reduced incidence of overuse injuries.

Introduction
Prescription of orthotics for individuals that have noticeable rearfoot pronation and calcaneal eversion angles is an accepted practice. In the case of athletes, these structural abnormalities usually lead to increased risk of injury as a result of the high demands placed on the musculoskeletal system. By definition a functional orthotics is designed to reduce abnormal foot motion or abnormal foot position. During the design of a functional orthotic consideration needs to be given to foot motion evaluated during dynamic activities as well as lower extremity alignment relative to the foot and point of application of the result force. This paper will give an overview of the challenges of performing accurate three-dimensional measurements of foot motion and the role of functional orthotic design in injury prevention.
Anatomical Description of the Foot

The ankle-foot complex is composed of 28 bones, which form 25 joints. Three functional segments can be identified in the foot: the rear-foot composed of the talus and calcaneus, the midfoot composed of the navicular, cuboid and three cuniforms, and the forefoot composed of the metatarsals and phalanges. The ankle joint is defined as the articulation between the distal tibia and the talus and the distal fibula and the talus. This joint is considered to have one degree of freedom defined by plantarflexion and dorsiflexion.

The subtalar joint is composed of three articulations. Motion of the talus is a complex screw like motion. The subtalar joint is considered to have one degree of freedom about an oblique axis (Figure 1). The motion at the subtalar joint has been described as pronation and supination. These actions are composed of three interdependent rotations, defining pronation as calcaneal eversion, talar adduction, talar plantarflexion and tibiofibular medial rotation. The reversed actions define supination of the subtalar joint.

Figure 1: Definition of rotational axis of the subtalar joint.

The transverse tarsal joint, also known as the midtarsal joint, is formed by the talonavicular and calcaneocuboid joints. This joint line divides the rearfoot from the midfoot. The motion produced at this joint is medio-lateral rotation and flexion-extension (Figure 2).
The last joints of interest are the tarsometatarsal joints. These joints place the metatarsals and phalanges in optimal position during weight bearing. To control excessive motion of the rearfoot, the transverse tarsal joint counteracts the action shown at the rearfoot. When the transverse tarsal joint is unable to sufficiently rotate to counteract the rearfoot action, the forefoot will lift off the ground through an inversion rotation about an axis at the second ray.

The interaction between joints in the ankle-foot complex adds to the difficulty of measurement of kinematic parameters of the rearfoot, midfoot and forefoot segments.

**Proposed Targeting Protocol**

Accurate measurement of foot motion is primarily limited by the size and structural characteristics of the tarsal bones. Placement of targets on individual tarsal and metatarsal bones of the foot is not conceivable. Tarsal bones are small in size, and some of them do not have a large area that is palpable and adequate for target placement.

Measurement of rearfoot relative to tibia motion and forefoot relative to rearfoot motion will provide sufficient information about foot mechanics that can be useful in the clinic. Target placement will be limited to landmarks in the rearfoot/midfoot and forefoot areas. Virtual targeting is used in this setting to allow for the measurement of more accurate foot motion than the standard clinical targeting protocols, which define the foot segment with only two targets. Virtual targeting uses 5 targets during dynamic trials and an
additional 3 targets during standing trials.

One limitation to this targeting protocol is the assumption needed to perform the mathematical calculation to define the motion, that of a rigid segment. The rigid body assumption is acceptable in most other human body segments, however, as was described above the foot is a complex of 28 bones and 25 joints. Even though this is a deficiency in the model, foot motion has been quantified to be accurately measured through this method.

Target placement is limited to the large capture volume characteristics of most walking and running evaluations. Targets approximately 8 to 10 mm in diameter are recommended for evaluations that include motion analysis of the forefoot and rearfoot segments. Larger targets could cause substantial merging of targets during the recognition process. Smaller targets could be lost from the field of view due to the large capture volume characteristics.

The placement of targets will define the axes of rotation and planes of motion of the respective segments. Shifting of targets can create an artificial offset in the angular measurements derived from the data collected. The calcaneus is the bone of the rearfoot most easily palpable and with the largest surface area. Due to the unobstructed view of targets placed on the lateral and posterior aspects of the rearfoot targets placed on this segment during dynamic trials are also the ones needed to define anatomical planes.

Dynamic targets placed on the rearfoot/midfoot segments are posterior calcaneus, lateral rearfoot and top of the foot (Figure 3). Dynamic targets placed on the forefoot are fifth and superior first metatarsal. The transverse plane of the rearfoot is defined by the posterior calcaneus, lateral rearfoot and medial rearfoot. The fifth and first metatarsal head targets define the medial/lateral axis of the forefoot.
Figure 3: Targeting protocol for rearfoot and forefoot motion analysis.

Joint coordinate systems are calculated from position data of the transformed anatomical targets. Euler angles are used for the calculation of three-dimensional angular displacement of the rearfoot relative to the tibia, and vector angles are used in the calculation of the forefoot motion relative to the rearfoot. These data will be used to evaluate range of motion and mechanical characteristics of foot motion during gait. Most evaluations include data collection of walking in a barefoot condition to examine the true tendencies of the rearfoot and forefoot segments during unconstraint motion. A second testing condition include running (low to medium speed) with athletic shoes. This section of the evaluation is designed to observe the mechanical changes that occur as a result of an increase in speed and the use of an athletic shoe. Parameters of interest include kinematic characteristics of the knee, ankle, and rear/forefoot joints, kinetic parameters based on ground reaction forces and center of pressure characteristics.

Functional Orthotics
Orthotics are devices designed to reduce or eliminate pathological stresses on the foot and lower extremity. Common practice is to prescribe orthotics for functional and structural deficiencies. A kinesiological evaluation is necessary to define passive ranges of motion and apparent deformities of the foot structure. A positive cast or impression of the foot is then obtained in subtalar neutral position. This positive impression is typically
used to design the functional orthotics. The suggested methodology includes the use of three-dimensional biomechanical data to analyze the foot and lower extremity mechanics under dynamic conditions. Forces acting on the body during walking and running tasks can significantly alter foot structural integrity which might not be apparent during static measurements or visual observation. Custom functional orthotics can be designed from a variety of shell and extension materials. Functional orthotics for use by athletes are most commonly made with a semi-rigid shell and PPT or plastozone extensions. The semi-rigid shell will help in the reduction of forces and motion control for the foot structure. Rear and forefoot posts are recommended based on the biomechanical data obtained during the walking and running evaluations. The posts are attached to the semi-rigid shell to control the abnormal motion of the foot. The rearfoot post controls the motion of the calcaneus at foot strike. The forefoot post support the forefoot structure to reduce compensatory motion of the subtalar joint during the stance phase.

The advantage of using high-speed three-dimensional kinematic and kinetic data for the design of the functional orthotics is the understanding of dynamic loading characteristics. Overuse sports injuries occur as a result of a maximum threshold of loading being surpassed. The loading characteristics and training practices are factors that will affect the risk of any athlete to sustain an overuse injury. Training practices are usually dictated by the coach and cannot be easily altered. However, loading characteristics can be analyzed and corrected through functional orthotics or pattern modifications.

Sample cases
Case one is from a collegiate athlete with a diagnosis of low back pain. Examination findings revealed a leg length discrepancy of 15 mm. The evaluation consisted of three-dimensional biomechanical test of the forefoot, ankle and knee kinematics and kinetics based on ground reaction forces and center of pressure data. The athlete was asked to walk barefoot and run with athletic shoes.

The results of the evaluation showed an asymmetric pattern in the vertical ground reaction forces on the left side during walking. The maximum deceleration magnitude was 112% body weight while maximum acceleration magnitude was 124% body weight. The right side showed a symmetrical pattern of 112% body weight maximum deceleration and acceleration magnitudes. Anterior/posterior ground reaction forces showed a symmetrical pattern of braking and propulsion bilaterally.
The center of pressure path indicated a slightly lateral deviation bilaterally, with the left side showing a medial progression over the forefoot. The left side also showed a fast progression over the rearfoot, spending most of the time over the forefoot segment. The right side demonstrated an even distribution of forces over the rear and forefoot.

Figure 4: Center of pressure path during walking barefoot.

Figure 5: Center of pressure vector distribution during walking barefoot.
Kinematics during walking indicated a more dorsiflexed forefoot on the left throughout the cycle. Inversion/eversion ranges of motion were symmetrical for left and right sides. At the ankle joint, dorsi and plantarflexion ranges of motion were symmetrical bilaterally, while the right side showed a higher range of inversion when compared to the left. No differences in kinematic parameters were found at the knee joint.

The center of pressure relative to knee joint center graph indicated better alignment of the right side when compared to the left (Figure 6).

![Figure 6: Center of pressure (COP) relative to knee joint center (KJC) during walking](image)

Vertical ground reaction forces during running showed a 50% body weight difference in maximum vertical force, with the right side reaching magnitudes of approximately 250% body weight and the left side magnitudes of 200% body weight. The right side also showed lower anterior/posterior ground reaction forces when compared to the left.

The center of pressure path demonstrated some characteristics of a forefoot runner, with all forces concentrated on the mid and forefoot areas (Figure 7). The right center of pressure path showed a more erratic pattern with greater medial lateral deviations.
The kinematic data showed a greater inversion range of motion of the forefoot on the left side when compared to the right. The left side also showed a greater range of motion in the dorsi/plantarflexion of the rearfoot relative to the tibia. When comparing the pattern of the center of pressure relative to the knee joint center during the running condition, the right side had the worst alignment with the greatest medial/lateral difference between the two parameters (Figure 8).
The data showed significant adaptations during both walking and running conditions. Asymmetrical force magnitudes and force distributions can contribute to the low back pain. Recommendations for this athlete were to reduce the leg length discrepancy by one half, and allow him to mechanically adapt to the new structure. Orthotics were design to stabilize the foot structure bilaterally and add shock absorption properties to the forefoot area to aid in the dissipation of forces to minimize the risk of an overuse injury over this segment.

Case two is a high school athlete with a diagnosis of multiple stress fractures of the fifth metatarsal, bilaterally. The first fracture occurred on the right foot, with 6 consecutive fractures on the left. The athlete is active in baseball and basketball.

The evaluation consisted of kinematic measurements of the forefoot and ankle motions and kinetics measures base on ground reaction forces and center of pressure data. Data was collected during walking barefoot, running and cutting with athletic shoes. Ground reaction force during walking indicated a less dynamic pattern on the left side when compared with the right. The anterior/posterior ground reaction forces were of lower magnitude on the left side when compared to the right. Kinematic data showed a greater range of motion of dorsi/plantarflexion of the left ankle when compared to the right. Inversion range was also higher on the left.

The center of pressure path showed a lateral deviation on the left, moving through the lateral border and fifth metatarsal sides (Figure 9).

Figure 9: Center of pressure path for walking barefoot condition
Vertical ground reaction forces during running were symmetrical right and left. Anterior/posterior ground reaction forces showed higher magnitudes on the right side versus the left. Kinematic data showed symmetric forefoot motion left and right, and a greater range of motion of ankle dorsi/plantarflexion on the right when compared to the left. Ranges of inversion/eversion of the ankle were comparable left to right.

The center of pressure path during running indicated a concentration of forces over the forefoot with a significant turning effect (Figure 10). The left side showed a slight lateral deviation of the path.

Figure 10: Center of Pressure path during running.

Ground reaction forces during side cutting showed balanced magnitudes between right and left sides. The center of pressure representation during a right cut (left foot pivot) showed the path in an extreme lateral position (Figure 11). The path rocked over the fifth metatarsal bone from foot contact to toe off, placing all the stress on one bone. The center of pressure representation during a left cut (right foot pivot) showed the path over the forth-metatarsal bone with a lateral contact point and a slightly medial toe off point.
Functional orthotics were designed using the results of the mechanical parameters from running and side cutting. The orthotics were posted on the forefoot to create a medial shift in the point of application of the result forces. The rearfoot was not posted, since adjustments of the forefoot will optimize the mechanics of the rearfoot. A deep heel seat was also designed in the orthotics to facilitate a longer dwelling period over the rearfoot and create a more adequate path of progression for the center of pressure over the entire length of the foot. A metatarsal bar padding was part of the orthotics to aid in the force dissipation over the metatarsal area and reduce the risk of another overuse injury.

Conclusions
Approximately 20% to 40% of running injuries can be attributed to structural abnormalities. Most of these structural abnormalities are apparent during weight bearing and exponentially increase the risk of injuries when high forces are generated. During weight-bearing the subtalar joint moves to absorb the imposed lower extremity rotations. When investigating the risk of injury associated with foot pronation, timing of the initiation of the pronation phase has been found to be of greater concern than the
range of motion. A detailed three-dimensional biomechanical evaluation is a valuable tool to help determine the timing of phases and range of motion. The study of frontal plane mechanics and the assessment of static measures have been shown to be insufficient to determine the functional biomechanics of the foot and ankle. Functional orthotics can be prescribed as a preventive measure to correct functional and structural abnormalities that might increase the risk of injury. Slight changes in force, frequency of loading, or speed of movement from normal practice for the athlete can trigger the occurrence of injury.

REFERENCES


