Basic Biomechanics of Ankle Foot Orthoses (AFOs)

To maintain the anatomical joints in a corrected position orthoses use two types of control systems, a GRF control system and a 3PP control system. This section will define these two force systems and illustrate their application to various applications involving orthoses.

1. Introductory Terminology

The forces directly related to ambulation (fig 1) include:

- muscle forces (Fm)
- ligaments forces
- joint forces (Fjt)
- gravitational forces (Wb) and inertial forces (Fi) which combine to form the Total Body Force (TBF)
- ground reaction force(s) (GRF)
- corrective force control systems:
* three point pressure control (F1, F2, F3)
* ground reaction force control (GRF)

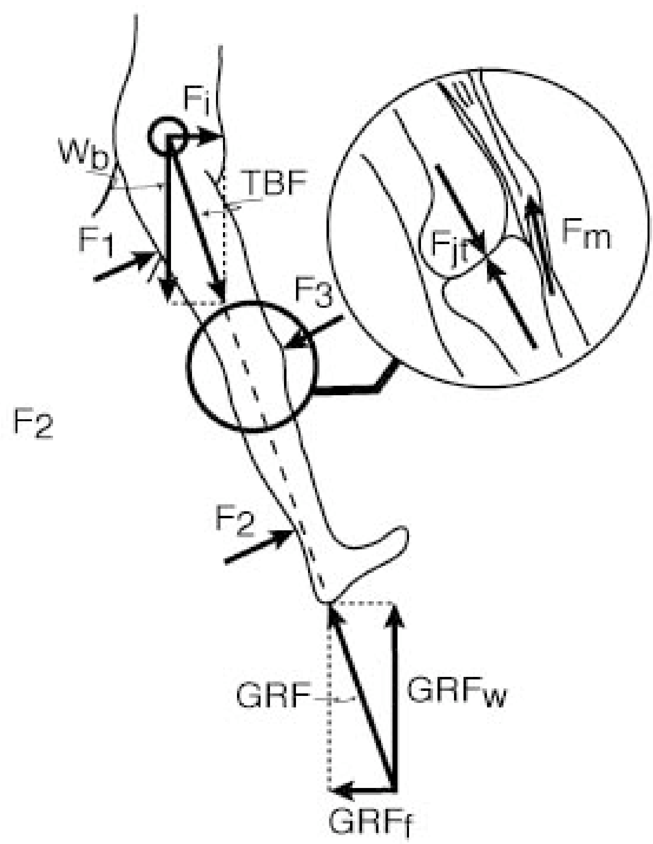

Figure 1. Forces on the body during ambulation

1. Corrective Control Systems

Corrective forces applied to the body may be classified under either of two force systems:
- a three point pressure control system (3PP control)
- a ground reaction force control system (GRF control).

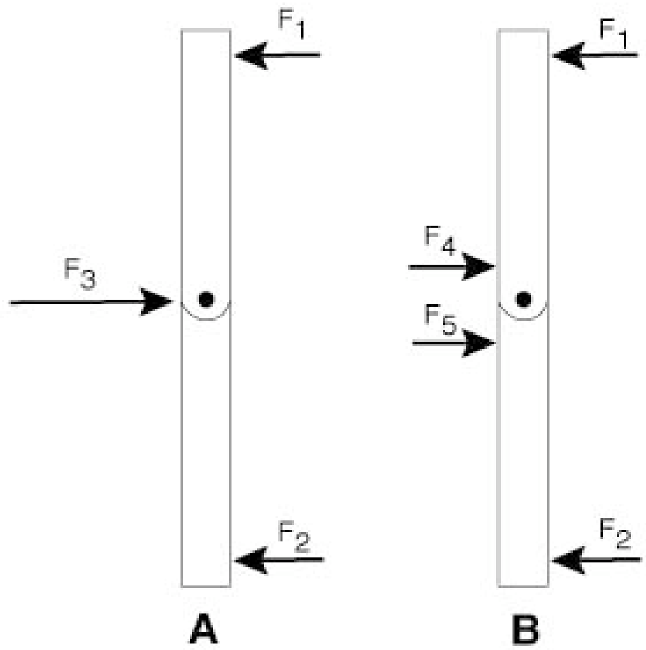

Figure 2. Three point (A) and four point pressure systems (B)

1.1. Three Point Pressure Control System (3PP control)

Definition
The use of an orthosis to stop or resist the rotation of two body segments about their shared point of rotation.

Description and Applications

- Two forces (F1, F2), one applied at the free end of each segment are opposed by a third force (F3) applied at the point of rotation (fig 2A).

- A variation of the 3PP control system which is more often used in orthotic practice is the 4 point pressure system (fig 2B). The central force is divided into two forces (F4, F5) because pressure is usually not tolerated directly on the anatomical joint and an orthotic trimline too close to the articulation may restrict motion.

- In orthoses, changing the lever arm or the surface area of the orthosis can alter the magnitude of a 3PP system as shown by the formula for pressure, (pressure = force / surface area). For example, in figure 3A, an AFO provides a 3PP system to prevent the foot from plantarflexing about the ankle axis due to the spastic triceps surae muscle (M triceps surae). The proximal lever arm (LA) of the orthosis is very short, and a relatively high corrective force is needed to prevent plantarflexion of the foot. The surface area of the calf bands is also small, resulting in relatively high pressures being exerted on the skin. Increasing the surface area of the posterior calf part of the AFO (fig. 3B) decreases the pressure on the skin. Increasing the lever arm (LA) of the orthosis (fig. 3C) also decreases the pressure on the skin by decreasing the magnitude of the force. The optimum solution for decreasing pressure is to maximize both the surface area and lever arm for any orthosis (fig. 3D).

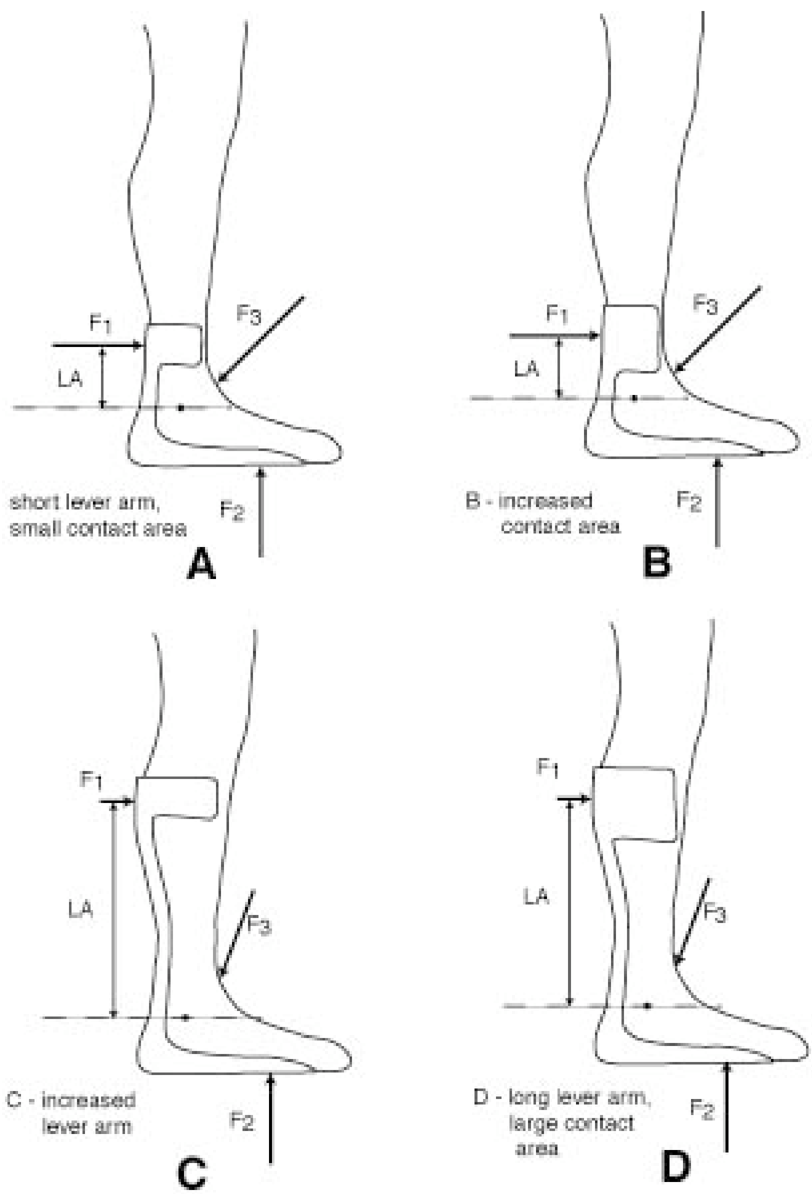

Figure 3. The effects of lever arm and surface area in AFOs

- A number of three point pressure control systems are employed by AFOs to prevent motion at the anatomical joints of the ankle foot complex. The three point pressure systems used to control ankle joint motion is a dorsiflexion (fig. 4A) or a plantarflexion stop and resist (fig.4B). Subtalar joint control requires an inversion (fig 4C) or eversion (fig 4D) stop or resist. Three point pressure systems are also needed to prevent forefoot abduction (fig.4E) and adduction (fig. 4F).

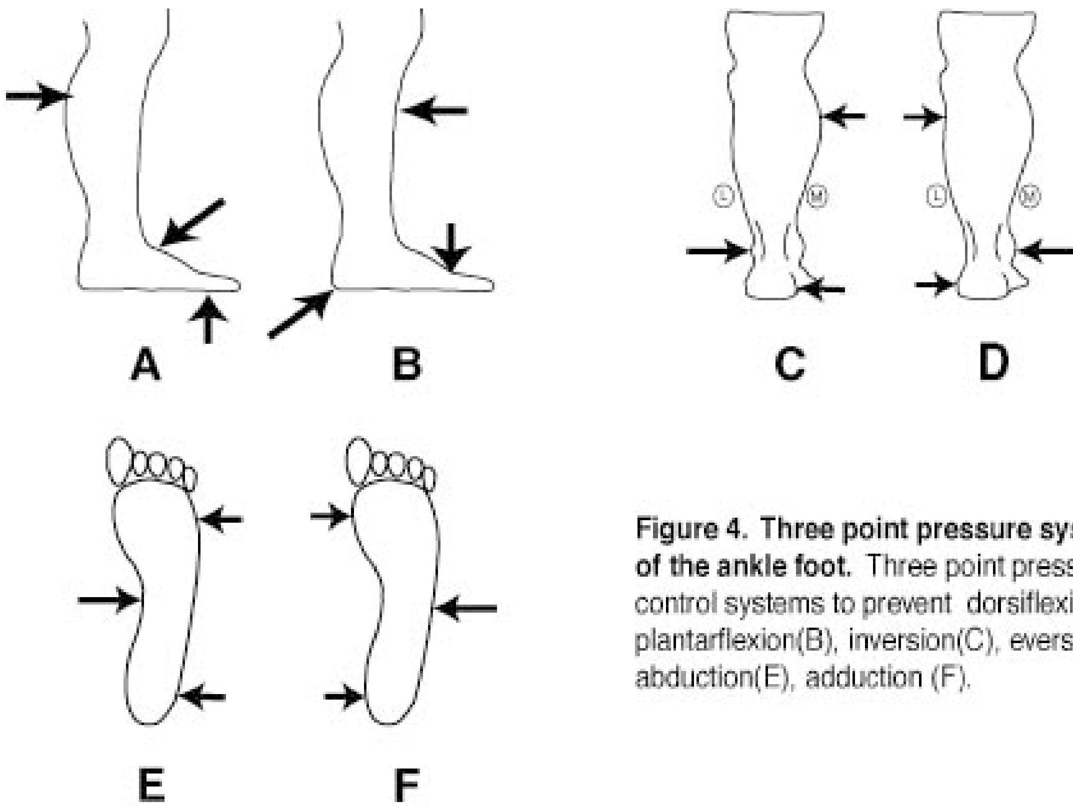

Figure 4. Three point pressure systems of the ankle foot. Three point pressure control systems to prevent dorsiflexion(A), plantarflexion(B), inversion(C), eversion(D), abduction(E), adduction (F).

2.2 Ground Reaction Force Control (GRF control)

Definition

The use of the GRF to control the motion of a body segment and/or joint with or without the use of an orthosis.

Description and Applications

- During swing phase, the foot and/or orthosis does not touch the ground and no GRF is generated (Fig 5A). When the foot or the orthosis/shoe combination contacts the ground, a GRF is applied by the ground to the lower extremity (Fig 5B, C). This application of the GRF to the lower extremity creates moments about the anatomical joints above. The resulting motion at the anatomical joints is dependent on the position of the line of action of the GRF and the movement available at the anatomical joints:

    * If the line of action of the GRF goes through the anatomical joint then no moment or rotational motion will be created about that joint. If the line of action of the GRF is aligned to one side of the anatomical joint then a moment is created about the joint. The GRF will

then rotate the segment about the joint unless it is restricted by counteracting moments from muscles, ligaments, bony blocks, etc.. In Figure 5B the line of action of the GRF goes posterior to the ankle axis producing a plantarflexion moment and if the plantarflexion moment is unopposed, the foot will plantarflex to the ground.

* If the movement at one anatomical joint is blocked by an orthosis, surgical fusion, spastic muscle, etc., the GRF creates a moment about the next free joint proximal to it. Figure 5C illustrates how the use of an orthosis and GRF control can prevent knee hyperextension. A rigid AFO blocks plantarflexion at the ankle at initial contact in the gait cycle. The action of the GRF is now transferred to the next free joint creating a flexion moment at the knee and preventing knee hyperextension at weight acceptance. It should be noted that the tibia rotates forward as the knee flexes increasing the lever arm of the GRF at the knee. This increases the flexion moment at weight acceptance and maximizes the GRF control of knee hyperextension at heel strike.

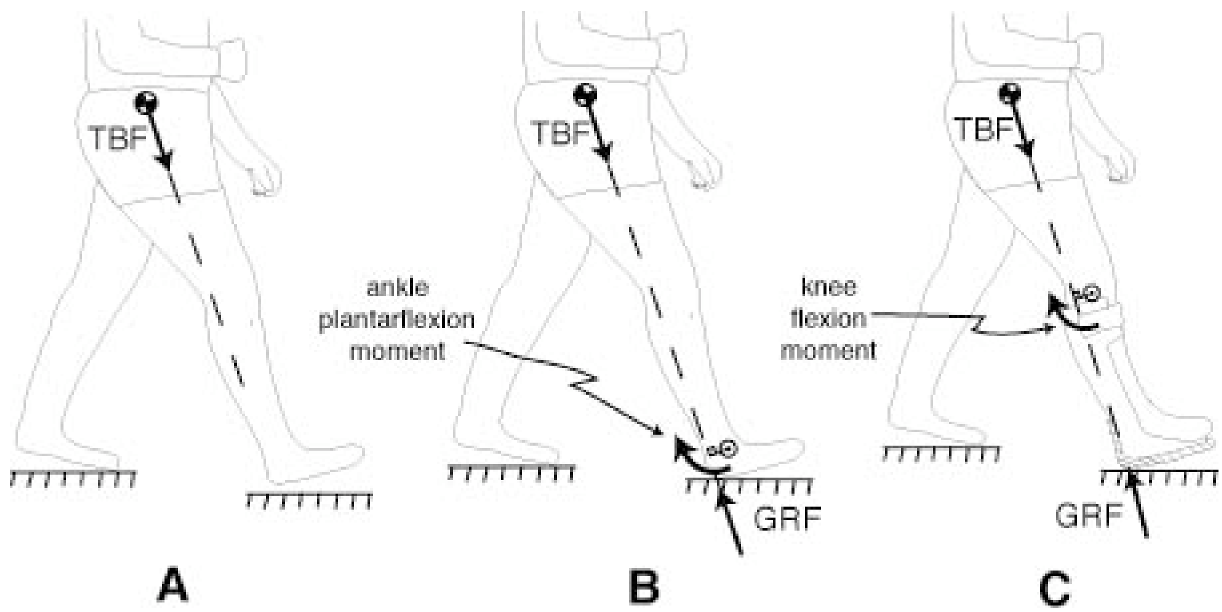

Figure 5. GRF control in the sagittal plane. Before heel contact no GRF acts on the lower extremity (A). At heel contact with no orthosis the GRF control acts to plantarflex the ankle (B). At heel contact with an AFO the GRF control acts to flex the knee.

- The previous example has investigated the GRF control system at foot contact in the sagittal plane. GRF control occurs throughout all the phases of stance and also includes motion in the frontal plane (Fig. 6). Figure 6A shows the pathological position for a valgus deformity of the subtalar joint. The line of action of the GRF is aligned lateral to the subtalar joint resulting in a large eversion moment. The application of a supramalleolar AFO with a medial buttress (fig 6B) moves the line of action of the GRF medial to the STJ at foot contact. A corrective inversion moment is generated to position the calcaneus in a corrected vertical position before weight acceptance at foot flat.

- GRF control is also used to control the trunk and upper extremities through standing frames, crutches, canes, walkers, etc.

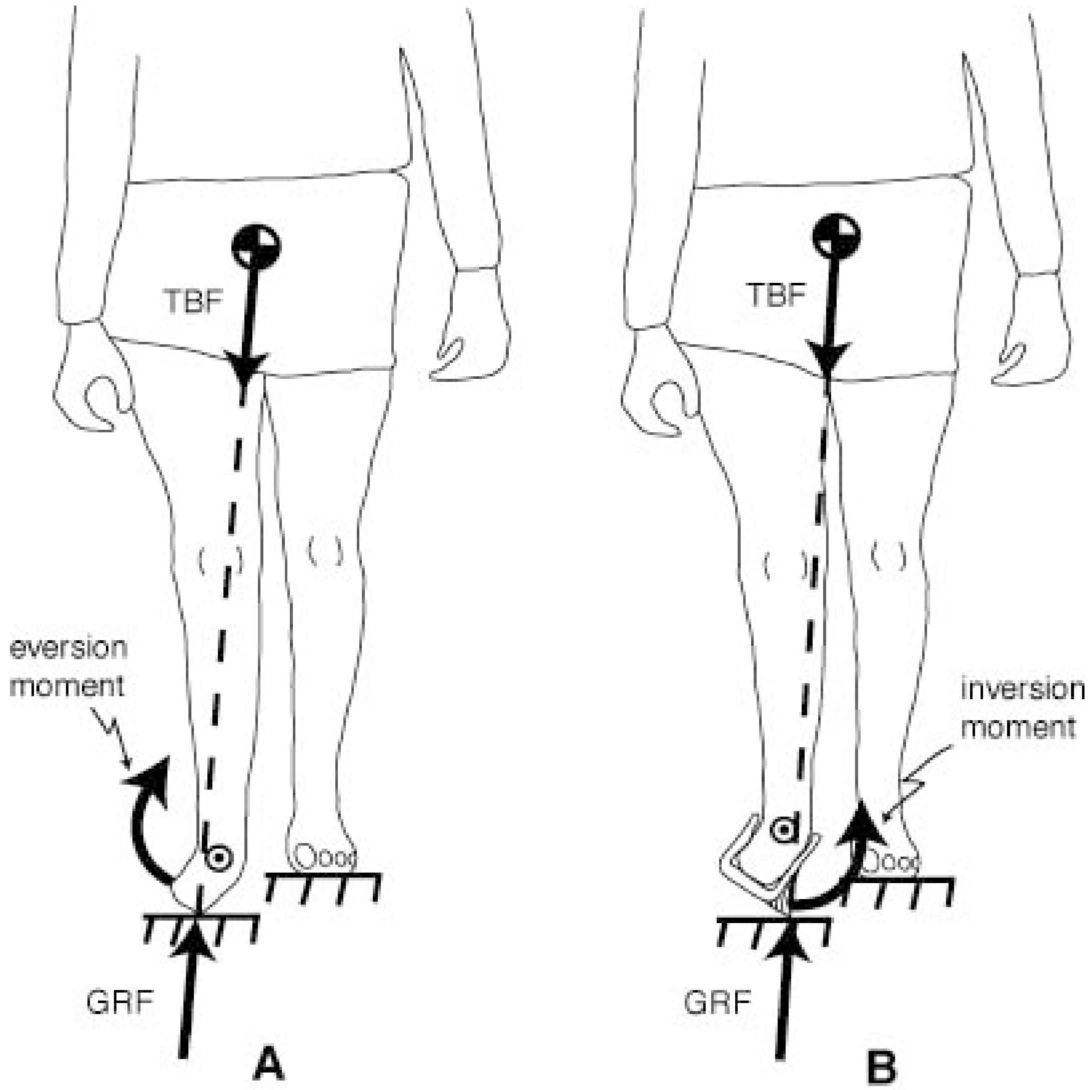

Figure 6. GRF control in the frontal plane. With a valgus deformity of the STJ at foot contact (A) the GRF produces an eversion moment increasing the deformity. The GRF control of a supramalleolar orthosis with a medial butress (B) produces an inversion moment which acts to correct the deformity.

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2.3 - Functional Differences Between GRF Control and 3PP Control

The following list compares the functional differences between the GRF and 3PP control systems (see detailed explanations (1 - 5) below):

GRF CONTROL	3 POINT PRESSURE CONTROL
1. dependent on contact with ground (stance phase only)	1. effective in all conditions (stance and swing phase)
2. dependent on shoe structure and interface	2. not dependent on shoe structure and interface
3. controls joints proximal to orthosis	3. controls joints within orthosis
4. less safe - joint stability dependent on terrain	4. safe - joint stable on all terrain
5. more efficient - may allow more motion of affected joint	5. less efficient - may restrict joint motion

1. GRF control of the lower extremity by an orthosis is only possible when the orthosis contacts the ground during stance phase. The 3PP control acts to control the motion at a joint during the entire gait cycle in both stance and swing phases.

For example a 3PP system from a plantarflexion stop orthosis is needed to control a drop foot during swing phase. A supramalleolar orthosis cannot prevent a drop foot during swing phase because it is only capable of applying a GRF control of the ankle joint and the foot is not in contact with the ground at this time.

2. The GRF control is dependent on structural strength of the shoe and interface between the shoe and the orthosis. The 3 PP control is not dependent on the structure of the shoe or the ability of the shoe to lock unto the orthosis.

For example the effectiveness of the GRF control on the STJ by a shoe/supramalleolar combination (fig 6B) is dependent on the structural strength of the shoe. If the side of the shoe or the flare (buttress) is weak and collapses under the force of the GRF then no correction of the STJ will occur. The effect of the GRF control will also be lost if the shoe slides over the orthosis after initial contact with the ground is made. The shoe will rotate until it is flat on the ground but the orthosis and foot within the shoe remain in a pathological position. More expensive sturdy shoes are needed for this orthotic application to maximize the effect of the GRF control. Neutral extrinsic heel posting added to the orthosis is essential to ensure that the shoe is fixed securely to the orthosis so that no motion occurs between the orthosis and the shoe.

The subtalar joint can also be controlled by a 3PP system of an AFO. Even if the shoe collapses or rotates on the orthosis at foot contact, the correction of the STJ is maintained by the 3PP system of the orthosis. The function of the orthosis is independent of the shoe structure and orthosis/shoe interface. The patient does not need to buy an expensive pair of shoe for use with this orthosis. Extrinsic heel posting which may add bulk to the orthosis is not needed for this application.

3. The GRF control creates a moment about the first free joint proximal to the orthosis through the application of forces to the segment below this articulation. The 3PP control can only control the motion of joints within the orthosis since a sufficient lever arm is needed on each side of the joint.

In the transverse plane, a supramalleolar AFO controls forefoot abduction/adduction through a 3PP system. The orthosis spans the foot for a sufficient distance on each side of the midfoot articulation to create the lever arms necessary to control the segments on each side of the joint. Although the plastic for this orthosis extends above the STJ, it only provides a GRF control of inversion/eversion (Fig. 6B). The plastic does not extend far enough above the STJ to create the needed lever arm for 3PP control of the STJ. On the other hand a rigid AFO with the proximal trim line extending up to the fibular heads has a sufficient proximal lever arm to produce 3PP control of the STJ.

In the sagittal plane an AFO with a plantarflexion stop controls ankle plantarflexion with a three point pressure system. The long levers on each side of the articulation make this a very effective 3PP control system. This orthosis demonstrates GRF control of the knee (flexion) at heel strike (Fig. 5C) through control of the segment (tibia) below the joint.

4. GRF control systems are less safe since stability of the corrected joint is dependent on what type of terrain you are walking on. The 3PP control system is much safer since it is not dependent on the type of terrain you are walking on.

If you are walking on a sloped surface or a very uneven surface then the position of the line of action of the GRF may shift and create a pathological instead of a corrective moment on the anatomical joint. The use of an orthosis with a GRF control does not protect you from this shift in the line of action of the GRF. Conversely, the use of an orthosis with a 3PP system control will act to protect this joint even when the pathological moment acts on the joint.

In the supramalloelar AFO example (Fig 6) the addition of the orthosis and shoe buttress shifts the line of action of the GRF from the lateral side of the joint (fig 6A) to the medial side of joint (fig 6B) resulting in a corrective inversion moment at the subtalar joint. The use of the supramalleolar AFO does not guarantee this corrective moment will always occur at foot contact especially when walking on uneven surfaces. If the braced foot in figure 6B lands on a rock toward the lateral side of the foot, the line of action of the GRF can shift laterally to the STJ resulting in an eversion injury. GRF control is dependent of the terrain you are walking on and therefore is not as safe as 3PP control.

A full length AFO uses a 3PP control system to control STJ motion. No matter how uneven the surface is the 3PP system will prevent excessive eversion at initial foot contact. Since the 3PP control also acts during swing phase, the foot is held in an ideal position for the landing at initial contact with the ground. The 3PP system maintains the position of the STJ through all phases of gait and is therefore safer than GRF control

5. In some cases the GRF control system does not restrict motion as much as a 3PP system control. This tends to make the movement using the GRF control more energy efficient than the 3PP control system.

For example an AFO with a dorsiflexion stop can be used to stabilize the knee in extension using GRF control. The use of the AFO in this case would also allow knee flexion in swing phase. An alternate orthotic method of restricting knee flexion is the use of a KAFO with a locked knee. The 3PP system which prevents knee flexion in stance phase would also prevent knee flexion in swing phase producing an inefficient walking pattern. The 3PP pressure system for maintaining knee extension with the KAFO is always available making it a very safe orthosis. The GRF control device (AFO) is more energy efficient but not as safe when compared to the 3PP control orthosis (KAFO) which creates a less energy efficient but safer gait pattern.