



Prosthetic Foot Design and the Gait Cycle



Mini-Documentary: [Safe Footing](#)

The amazing foot, an amalgamation of tendons, ligaments and bones, has been an enigma to those trying to replicate its use and movement in the design of the prosthetic foot.

The human foot comprises 26 bones, 33 joints, 19 muscles and 107 ligaments. Both feet make up 25 percent of the bones in the body.



Figure 1: The Niagara Foot

Physiologically, the human foot gets its strength and rigidity from the skeleton, tendons provide alignment and strength, and the foot muscles absorb and release the energy that provides locomotion when signaled by the brain. In the case of an amputee, the limb directs the energy to the prosthesis, which in turn should replicate the movement of a natural foot in the gait cycle.

The Niagara Foot, showcased in the mini-documentary, “Safe Footing,” was borne of a vision of a prosthetic foot that would closely mimic the biomechanics of the human foot—providing strength, agility, flexibility and comfort—at an affordable cost for those living in under-served areas of the world. The



The Gait Cycle

There are two primary actions in the human walking gait cycle: the stance phase and the swing phase (Figure 2).

1. **Stance Phase** is the time when the foot is on the ground. Comprising about 60 percent of the walking cycle, both feet will be on the ground for a period of time during this phase.
2. **Swing Phase** occurs when one foot is on the ground and one in the air. The foot that is in the air is said to be in the “swing” phase of gait.

Within the stance phase are the five sub-stages that a single foot travels in the gait cycle:

Heel Strike starts the moment when the heel first touches the ground and lasts until the whole foot is on the ground (early flatfoot stage).

Early Flatfoot begins the moment that the whole foot is on the ground and ends when the body’s center of gravity (located approximately in the pelvic area in front of the lower spine when we stand and walk) passes over top of the foot. Here the foot serves as a shock absorber, helping to cushion the force of the body weight landing on the foot.

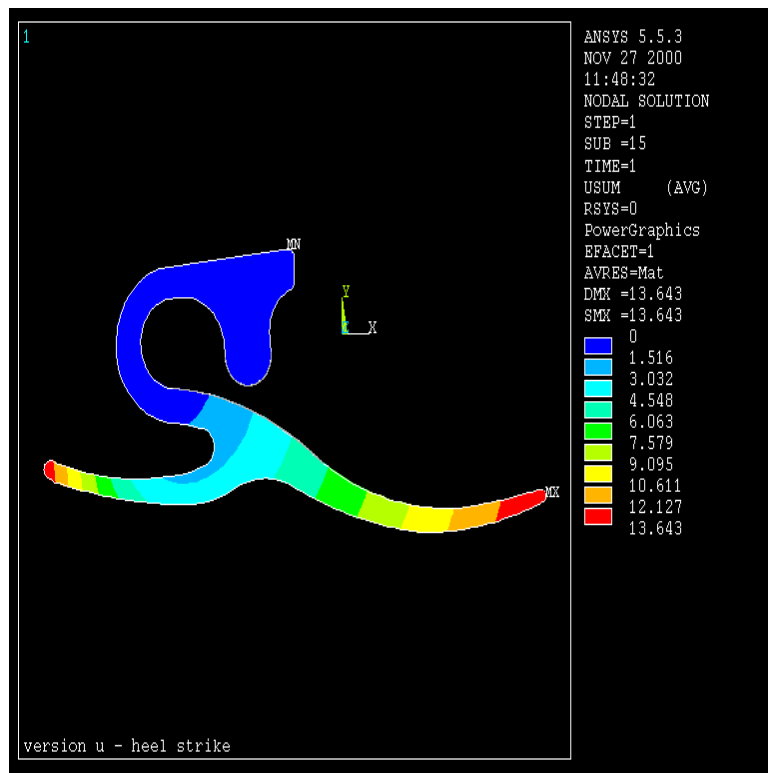
Late Flatfoot begins once the body’s center of gravity has passed in front of the neutral position and ends when the heel lifts off the ground. Here the foot needs to go from being a flexible shock absorber to being a rigid lever that can serve to propel the body forward.

Heel Rise begins when the heel begins to leave the ground. Here the foot functions as a rigid lever to move the body forward. During this phase of walking, the forces that go through the foot are quite significant—often 2-3 times a person’s bodyweight—as the foot creates a lever arm (centered on the ankle), which serves to magnify bodyweight forces.

Toe Off begins as the toes leave the ground. This represents the start of the swing phase.

successful realization of that vision resulted from a collaboration that drew from the strengths, ingenuity, and determination of multiple parties: Inventor Rob Gabourie, a Canadian board-certified prosthetist and the owner of Ontario-based Niagara Prosthetics and Orthotics International Ltd. (NPOI); researchers at the Human Mobility Research Centre at Queen’s University and Kingston General Hospital, Centennial Plastics Mfg. Inc., who contributed molding and tooling expertise; and DuPont polymer engineers who provided polymer recommendations and mold flow testing.

The project had several iterations fraught with failures. The polymer engineers at DuPont initially thought it was going to be a relatively straightforward approach using one of their engineering thermoplastics. However, it became apparent after several failed tests that this application was far more complicated than originally anticipated.



The scientists discovered that the Niagara Foot required a material that could store and release energy in a controlled, nonlinear way to meet the rigors of long hours and abuse over rough terrain. The DuPont team finally found the solution in Hytrel®, a material that acts like an energy sponge—capable of absorbing and releasing the energy to provide the stiffness and flexibility necessary for this complex application. Hytrel® characteristics provide smooth actions, reducing biomechanical impacts on the residual limb.



Biomechanics of the Niagara Foot in the Gait Cycle

The Niagara Foot (now in its next generation named the Rhythm Foot) is designed specifically for individuals with active lifestyles and those who walk on rugged ground. A key aspect of its design lies in its keel – a single, S-shaped part that is injection-molded from Hytrel® 8238, which acts like a spring to provide energy storage and return during the gait cycle.

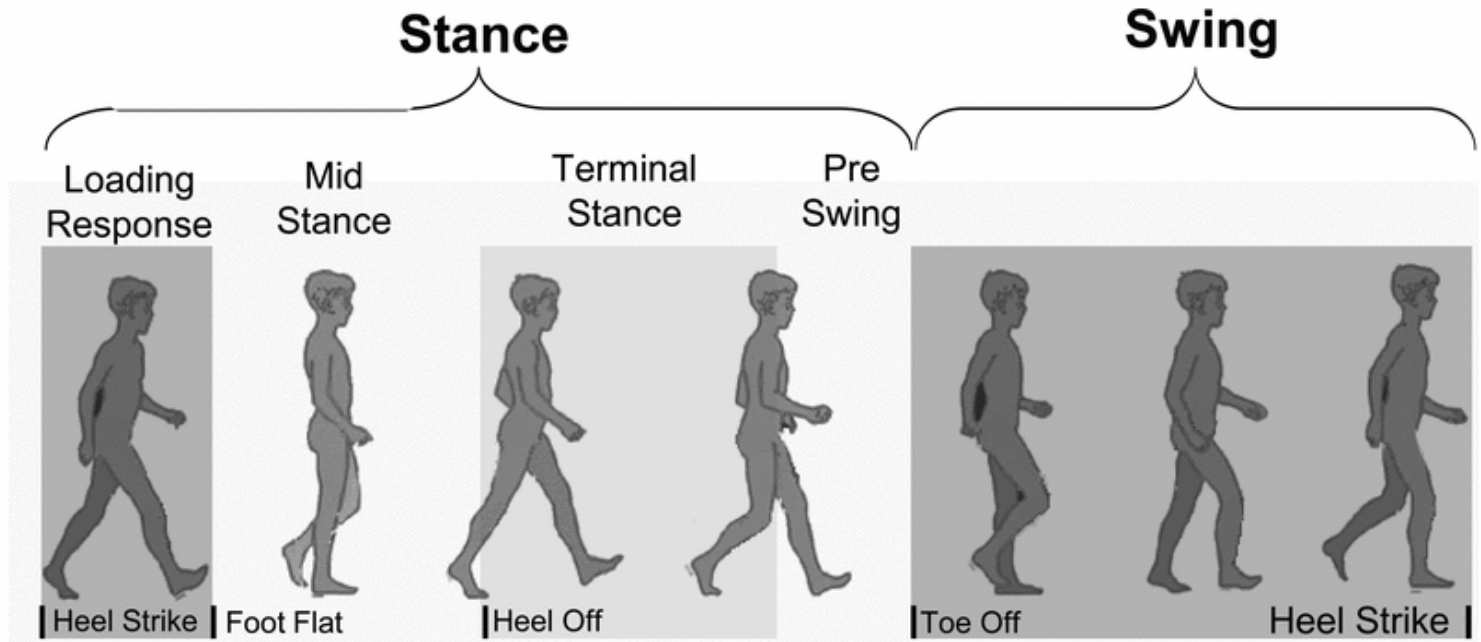


Image courtesy of U.S. Dept. of Veteran Affairs

Figure 2: The Gait Cycle

The keel has five main sections: the Platform, Dynamic C Coil, Horns, Heel Lever and the Forefoot Lever (see Figure 1). Each section works to mimic the movement of the human foot throughout the stages of the gait cycle:

- **Heel Strike** – The platform starts to open and flex upwards. At the same time, it opens the gap that is between the platform and the horns. That motion relies on having the proper flexibility in the Dynamic C Coil.
- **Early Flatfoot** – As the foot moves into mid-stance and the patient moves forward, the foot is placed in neutral, with floor contact at both the heel and the forefoot. This causes the gap between the platform and horns to close, making the system stiffer but maintaining some flexibility.
- **Late Flatfoot/Early Heel Rise** – At this stage, the horn and the platform come in contact, which helps to transfer energy to the Forefoot Lever for the Heel Rise.
- **Toe Off** – In this phase of the cycle, the Forefoot Lever is loaded, transferring energy into the follow through phase of the cycle

Energy release and reabsorption are critical elements in the biomechanics of the foot. Hytrel®, with its stiff yet flexible properties, was able to provide the fluid motion required for an affordable, durable and comfortable prosthetic foot.