Limb Preservation, Gait Restoration
Considerations in the Comprehensive Management of Partial Foot Amputations

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Introduction

A practitioner from Texas said it best: “It seems like I’m reinventing the wheel every time I do a partial foot.” A literature review shows any number of techniques suggested to help preserve the at-risk partially amputated foot, but none could be found that address all the issues involved in limb preservation and in the restoration of function of the locomotor system.

This article will attempt to define the issues involved in the orthotic/prosthetic management of partial foot amputations and provide a pathway to resolve those issues. So what are the issues? First and foremost is the preservation of the limb – to create an environment that will optimize the management of stresses contributing to destructive forces on the foot, namely pressure, friction and shearing forces. Equally important is the management of issues relating to the restoration of gait function, those being functional biomechanics, center of gravity, limb length and propulsion considerations. These issues must be managed to restore the function of the foot and return it to its role as a stable dynamic propulsive lever arm.

It should be noted that these two goals are not mutually exclusive or contradictory, but are rather synergistic and complimentary. The better foot preservation is managed, the easier it becomes to restore gait function. Each enhances the functional outcome of the other.

Before we proceed, a discussion on terminology is necessary to communicate the concepts contained in this article. The one important term used consistently in this article is “functional posture.” Functional posture is defined as that posture from which tri-planar closed chain movement and function is allowed to occur. Why tri-planar motion? Because function, by definition, involves motion occurring through all three planes of motion at the same time. The foot-ankle complex can not function unless it is pronating and supinating – that is, going through three planes of motion at the same time.

Functional posture is an important consideration in the design and application of any orthotic device. It should be contrasted to “static alignment” or immobilization. Static alignment certainly has a role in the orthotic management of fractures and other post-surgical applications when immobilization is required to facilitate healing. But while appropriate in these situations, static
alignment – e.g. immobilization – actually serves to inhibit dynamic function and makes closed chain function less stable.

The other term used in conjunction with this subject is "stability." What is the definition of "stability"? It seems most would agree that uncontrolled motion exceeding normal limits of range of motion equates to instability. The term is commonly used as a synonym to immobilization; e.g. immobilization equals stability. However, a strong argument can be made that the exact opposite is true – that immobilization creates instability during gait. With no motion there can be no proprioceptive stretch reflex, and with no stretch reflex there can be no reactive muscle activation, and with no muscle activation, there can be no chain reaction creating functional stability. If the distal segment is not propulsive or is not adapting to the terrain or to top-down or external forces, then gait becomes an adaptive series of proximal compensations instead of dynamically stable functional ambulation. Immobilization causes as much instability as uncontrolled motion exceeding normal ranges of motion. Stability, therefore, is defined as controlled motion occurring along biomechanically appropriate pathways within normal ranges of motion.

Finally, the focus needs to be on closed chain function as opposed to open chain motion.

Function occurs as gravity drives (actually pulls) the body into the ground, driving the calcaneous from an inverted to an everted position in the frontal plane. This triggers the process of the foot transforming from a more rigid supinated foot to a more flexible pronated foot to allow for adaptation to the terrain. These tri-planar motions are driven by gravity, and function is allowed to occur secondary to gravitational forces driving those tri-planar motions. It is the motions of that biomechanical event that trigger the stretch reflex component of the proprioceptive system. This reflex fires muscles to first eccentrically decelerate gravitational forces, so that they can then function concentrically to create propulsion – the "squat before jump" concept. Function IS closed chain. The appropriate orthotic environment is one that allows the biomechanical event to occur so the proprioceptive event occurs so muscles fire to control gravitational and other external forces to create dynamic functional stability.
**Limb Preservation**

Dealing with a partial foot amputation is a challenge, partially because many partial foot amputations are secondary to systemic diseases that leave the foot “at risk” for further breakdown. If a foot becomes avascular from any disease process, amputation may be the only remaining option regardless of prosthetic management. Many of these diseases are progressive, so no matter how the amputated foot is managed, there is always the potential for secondary amputations if the disease process progresses in the residual foot. The average time between the initial and the second amputation is only two years.

There are many other amputations where there is adequate arterial supply and venous return, but the foot is insensate and cannot feel pain or pressure. The patient has no sensation at all that there are destructive forces working on the residual foot. This may lead to soft tissue damage that can occur within 30 minutes of the application of those destructive forces. These same patients may lack adequate proprioception and may feel clumsy during gait, leading to the potential for additional damage to soft tissue.

Therefore, the role of the orthotist/prosthetist is to create an optimal environment that serves to preserve the integrity of the residual foot, knowing that systemic diseases may thwart the best of those efforts.

There have been numerous types of devices created to manage the partial foot amputation. A recent edition of a book *Partial Foot Amputations, SÖderberg et al* on partial foot amputations illustrates some 44 potential design options. These can generally be cataloged into three very broad categories: carbon fiber footplates, either built into shoes or put into shoes with filler prosthesis (Figure 1), simple sockets with filler prosthesis, some more cosmetic than others (Figure 2), and immobilizing devices, comprised of either essentially leather lined solid ankle AFOs (Figure 3) or carbon fiber devices (Figure 4) that are much lighter in weight. Some are hybrids of all of the above.
While most of these devices address some of the issues relating to prosthetic management of the partial foot amputation, none addresses all of the issues relating to limb preservation and gait restoration. No matter how hi-tech the materials, some of them leave us with the functional equivalent of wooden peg-leg devices utilized in the middle ages. The following will describe a comprehensive method of managing the integrated issues of limb preservation and gait restoration.

Friction

Friction is defined as the movement under pressure of one surface against another surface. This can occur if a socket is fabricated too large so that the residual foot moves within that socket. If friction is allowed to occur, blisters may form that could lead to skin breakdown (Figure 5). Care must be taken in socket fabrication to assure completely even pressure distribution of the foot within the socket so as to contain the residuum without allowing it to move within the socket.

Pressure

It only takes about 27 mmHg of constant pressure to occlude blood vessels and deprive tissue of fresh oxygenated blood supply. Constant pressures at this level for 30 minutes or more can lead to loss of tissue viability and the onset of wounds that can lead to secondary amputation. Care must be taken in socket fabrication to assure that all pressures are equally distributed over as wide an area as possible (Figure 7) to prevent pressure exceeding that which soft tissue can withstand.

Ill-fitting footwear that is shaped wrong (wrong last), or is too small or too narrow can also lead to excessive constant pressure on the
residual foot (Figure 8). Care must be taken to assure that footwear does not induce excessive pressures on soft tissue.

Finally, the partial foot prosthesis can induce pressures into the socket, especially during the third rocker or the propulsive phase of gait. As the forefoot is dorsiflexed, intermittent pressures can be transmitted into the socket (Figure 9). A break should be incorporated into the prosthetic filler to absorb the forefoot dorsiflexion forces and prevent those forces from being transmitted into the socket.

Shearing forces
Shearing forces are perhaps the most destructive of all forces on the partially amputated foot. Anatomical shearing is created by bone moving on the inside of the skin, creating soft tissue breakdown from the inside out. It is shearing forces that generally lead to callus formation. These calluses can be problematic in traumatic partial foot amputations, but can be destructive enough to lead to the next level of amputation in the diabetic patient if “invisible” ulcerations occur underneath the callus. Shearing forces may be the primary cause leading to the vicious cycle of ambulation, skin breakdown, non-weightbearing healing, ambulation, etc.

In understanding shearing forces, consider the foot as a series of lever arms. Normally the forces of the large gastroc/soleus complex cross the ankle to control the relatively long lever arm of the mid/forefoot. Conversely, the forces of the smaller anterior group cross the ankle and control the relatively shorter rear foot lever arm (Figure 10). Because the power of the muscle groups correlates to the length of the lever arm, the foot is biomechanically balanced.

However, when the anterior lever arm is shortened by amputation to any level, the remaining lever arm is now too short relative to the strength of the posterior muscle group. Normal muscle contraction overpowers the now too short lever arm, thereby creating increased pressure and shearing forces leading to callus formation and skin breakdown (Figure 11). The intervention objective is to restore the functional length of the lever arm to eliminate shearing forces and recreate functional balance, thereby protecting the distal end of the residual foot.
Filler prostheses, as necessary as they are to fill out the shoe to keep the shoe from collapsing, do not serve to lengthen the lever arm (Figure 12).

Carbon fiber foot plates are commonly used to restore some function to the foot. Because these carbon fiber footplates bend wherever force is applied, they tend to disperse and deflect those but do not direct those forces. Therefore it is believed these serve only to partially lengthen the lever arm (Figure 13).

No research has demonstrated that carbon fiber footplates resolve shearing forces, and preliminary research indicates that significant forces still exist at the distal end of the residual foot (Figure 14) during gait. Clinically it has been all but impossible to find a foot managed with a carbon fiber footplate that does not still have callus formation.

In a similar fashion, articulating dorsiflexion assist AFOs have been used to help manage the partially amputated foot, especially those with concurrent neuromuscular deficit. These devices, too, have never been proven to manage shearing forces and preliminary research indicates that they do little to mitigate those destructive forces (figure 15).

To protect the distal end of the residual foot by eliminating callus formation and eventual ulceration, the goal is to restore the length of the lost lever arm. To do this, a carbon fiber footplate was engineered that is more stable at the midfoot with the dynamics tapering down towards the toe to direct the forces of propulsion towards the shoe break. A lateral strut was attached to the footplate to act as a dynamic functional lever arm. It is attached to an anterior shell to dissipate the forces that are accumulated during the loading phase of the gait cycle.

There are a number of pre-fabricated carbon fiber AFOs available that conceivably could work to restore lost lever arm function. They use various combinations of medial and lateral struts with either anterior or posterior shells.
In principle, a lateral strut is generally preferred to a medial strut. The foot is supposed to pronate at initial contact during normal function, so that motion would be away from a lateral strut. The one situation when a medial strut is preferred is in dealing with a very high arch Pes Cavus type foot, when dorsal foot structure would impinge on a lateral strut, and then only if alignment can not resolve that issue in a lateral strut device.

An anterior shell is also preferred to a posterior shell. Most of the shearing forces occur during gait in the third rocker. To deflect those forces, an anterior shell is needed to adequately disperse them through the shell to a large distribution area over the entire anterior aspect of the tibia up to tibial tubercle height.

One device meets the criteria of a lateral strut – anterior shell and it is not a prefab AFO. The ToeOFF (Allard USA, Rockaway, NJ) is a fiberglass/carbon fiber/Kevlar® composite shell engineered as a component to be customized into an AFO or a partial foot prosthetic device (Figure 16). The footplate has been engineered to direct the forces of ambulation towards the shoe break. The lateral strut has been engineered to load potential energy and transmit those forces in the anterior shell. The anterior shell comes to tibial tubercle height to optimize the lever arm function of the device and to distribute those forces over as wide an area as possible.

In the case of managing the partial foot, the socket is attached to the footplate to manage shearing forces. Alignment of the socket to the footplate is critically important to optimize function and patient comfort. The anterior shell is aligned to the tibia, and then the socket is placed on the footplate to maintain that alignment to assure even pressure distribution from top to bottom of the pre-tibial shell. A soft interface must be added to the interior aspect of the anterior shell to assure the rigid shell does not lead to skin breakdown along the tibial crest. The SoftKit, ComfortKit or SoftSHELL (Allard USA) all serve this purpose.

Of the products in the ToeOFF family, the ToeOFF generally is appropriate to handle moderate stresses, and the Blue Rocker is more appropriate to handle more severe stresses. Because of the lever arm replication needed to handle the partially amputated foot, the Blue Rocker is usually the product of choice to manage TMA, Chopart or Lisfrank amputation levels. The ToeOFF would generally be most appropriate if just the first ray or two are amputated. It is thought that a carbon fiber footplate with fillers would be sufficient to manage toe amputations.
One unique aspect of the ToeOFF is that each size has its own unique dynamic response. As the product size increases, the level of dynamic response also increases. The Blue Rocker is a heavy duty ToeOFF. It is sized to the pre-amputated size of the foot unless the patient is overweight and needs extra support for greater proximal control. If the patient is significantly obese, then choosing a size larger than the pre-amputated size would offer greater levels of support that would be more appropriate to the dynamic response needs of the patient.

With the support of these lever arms (foot plate into lateral strut into anterior shell) the forces normally focused on the distal end of the residual foot are now sent distal to the residual foot, thereby managing the shearing forces that can lead to disruption of soft tissue (Figure 17). In addition, the progression line is much longer in this environment than in either the carbon fiber footplate or the dorsiflexion assist AFO.

This system of a socket on top of a Blue Rocker can serve to manage the destructive forces of pressure, friction and shearing forces, providing the best option in attaining limb preservation goals.

Gait Restoration

Gait restoration is as important a consideration as limb preservation in dealing with the partial foot amputee. Typical deficits in this population include Limb Length Discrepancy (LLD) leading to compensations such as asymmetrical trunk lean, less time in single limb stance on the involved side compared to the uninvolved side, and inhibited frontal plane pelvic stability. As the involved side is relatively apropulsive, propulsive forces involved in ambulation are potentially induced as excessive forces into the uninvolved side, putting it at greater risk. Because gait is no longer symmetrical and fluid, energy consumption is thought to increase, so distance capacity and endurance are diminished. Every effort needs to be made to restore gait to a dynamic, balanced, fluid process of ambulation.
Biomechanics

In fabricating the socket, an important consideration is to make sure the calcaneous is able to function in the frontal plane by passing through subtalar neutral from some degree of inversion (nominal 8 to 12°) during swing to some degree of eversion (nominal 5 to 7°) during stance (Figure 18 Right posterior view). This motion is critical to proximal functional stability during gait because proximal stability is interdependent on normal biomechanical function distally. Therefore the posterior aspect of the socket should function as a biomechanical foot orthotic device to allow normal function of the calcaneous in the frontal plane. The heel cup should only be as firm and as deep as necessary to prevent excessive motions while allowing normal biomechanical function driven by gravitational and ground reaction forces to occur.

Center of gravity

The center of gravity (COG) in partial foot amputation populations has been shown to have shifted towards the uninvolved side (Figure 19). This can be addressed by restoring limb length and functional stability on the involved side. The classic test is to assess trunk sway during ambulation. As a person walks, the transfer of the center of gravity from the propulsive side to the now weight-bearing side should be absorbed at the hips. The trunk is to be relatively stationary in the frontal (coronal) plane during ambulation. Optimizing limb length and biomechanical function of the involved side will help facilitate more normal function in the transfer of COG from one limb to the other during gait, thereby minimizing deviations to COG and trunk sway during gait.

Limb length

In partial foot amputations, modern surgical techniques generally are able to maintain normal ROM at the ankle in the sagittal plane. As forefoot structures are lost, corresponding rear-foot releases are also done to avoid the ankle losing ROM towards dorsiflexion. However not all patients have benefited from these techniques, so one of the first issues to managing the partially amputated foot is to provide appropriate functional posture for the residual foot in the sagittal plane.
With the foot in its functional posture in static stance and the ankle at 90°, two observations can be made. The first is that there should normally be about 20° of ROM towards dorsiflexion and about 40° of ROM towards plantarflexion (Figure 20).

The second observation is that in this neutral posture, the normal calcaneal angle is about 40° (Figure 21). It is forefoot and midfoot osseous structures that help maintain that rearfoot calcaneal angle.

With each progressive level of amputation, more and more supporting osseous structure is lost and the ankle drops into plantarflexion. As the ankle drops into plantarflexion, the calcaneal angle not only drops but the calcaneous also glides to the posterior, in effect moving out from underneath the talus and tibia. The result is an increasing amount of limb length loss with each progressive level of amputation (Figure 22 Transmetatarsal, 23 Lisfranc, 24 Chopart). This acquired malleolus to floor limb length discrepancy (LLD) can reach 1 1/2" at the Chopart amputation level. Creating appropriate functional posture at the ankle in the sagittal plane will help restore this lost limb length and help restore functional ROM, and in the process restore the calcaneal angle back to a functional posture of 40°.

To determine available ROM, a closed chain assessment is necessary to link calcaneal eversion with maximum ankle dorsiflexion. An open chain assessment of ROM towards dorsiflexion without calcaneal eversion will come up short in determining available motion, so a closed chain assessment is much more accurate. Place a board under the involved side and place the residual foot on a prefab foot orthotic shell to minimize the foot sliding on the board. With the patient in bi-pedal stance, elevate the board until the posterior calcaneous begins to elevate off the board. This is maximum ankle dorsiflexion (Figure 25).
there is normal ROM available, the calcaneal angle will be about 60°. If that is the case, drop the angle to about 40°. This is the optimal functional posture for the ankle in the sagittal plane.

If there is less than 60° towards dorsiflexion available, drop the angle 1/3 of total available to re-establish the 1/3 to 2/3 ratio (Figure 26). This will leave the limb with a residual limb length deficit.

Three benefits are derived from finding this optimal functional posture. The first is that this positions the patient so that normal sagittal plane ROM will be available towards both plantarflexion and dorsiflexion during gait. The second is that this posture will help alleviate the acquired LLD. Finally, repositioning the calcaneous closer to its normal postural angle will reposition the fat pad back under the calcaneous, restoring its padding and shock absorbing function.

Now that this posture is determined, the residual foot is cast in the standard 90/90 posture with the ankle in its corrected functional posture in the sagittal plane. The socket is now fabricated with anterior posting to maintain this sagittal plane functional posture. If the ankle is posted to its corrected functional neutral posture, LLD issues should be resolved. If there is a lack of ROM towards dorsiflexion and the new functional posture of calcaneous in the sagittal plane is less than 40°, then additional posting may be needed under the posterior aspect of the socket (Figure 27) to restore malleolus to floor limb length.

**Filler prosthesis**

Once the socket is fabricated and posted for sagittal plane functional posture and frontal plane function for the calcaneous, a filler prosthesis is incorporated onto the socket to fill out the shoe. If the uninvolved side tends to be pes-planus, the filler prosthesis should be relatively flatter. If the uninvolved side tends to be pes-cavus, then the profile should be higher to match that profile. The filler prosthesis should “fill up the shoe” just like the contra-lateral foot does.

One other consideration in the fabrication of the filler prosthesis is the elimination of the prosthesis pressing into the socket during the 3rd rocker or the propulsive phase of gait (see discussion under “Pressure” above). As the heel comes up off the ground and the shoe flexes, the prostheses can exert pressure into the socket (see figure 9). To avoid this source of pressure into the socket, a break point is added at the met-head line or at the shoe break. This break point, filled with a very low durometer foam, will collapse during the third rocker, thereby reducing the pressure being transmitted into the socket.
The posterior aspect of the socket works as a biomechanical foot orthotic device to help manage sagittal plane function of the calcaneus. The anterior aspect of the socket should come high enough to transition into the filler prosthesis to match the height profile of the other foot. This will also serve to protect the usually fragile skin on the distal residual foot (Figure 28).

**Propulsion**

The foot that has been partially amputated has lost the anatomical lever arms that served to facilitate propulsion during gait. These patients have lost the “spring in their step.” The foot has lost its intrinsic ability to get itself off the floor, so now it has to be lifted off the floor by proximal forces and compensations. This leads to asymmetries during gait that is thought to increase energy consumption and decrease distance capacity.

The restoration of the propulsive aspects of gait utilizes the same lever arms used in the management of shearing forces involved in partial foot ambulation (see Shearing forces, figure 16 above). As the tibia moves forward over the fixed foot, the dynamic lever arms of the Blue Rocker load potential energy. As the heel comes up during the gait cycle, that energy is released to spring the foot off the floor. Propulsive dynamic gait and the ability of the foot to spring off the floor (Figure 29) have been restored.
Fabrication Requirements

The prosthetic fabricator will need to know you will be mounting the socket on a Blue Rocker. In addition, the fabricator will need to have the following:

- A physical model or cast of the residual foot. (Crush boxes will not show the contours of the anterior aspect of the residuum so are not appropriate.)
- A tracing (or cast) of the contralateral foot to match length and width
- A tracing (or cast) of the contralateral foot to match sagittal plane profile
- The degree of posting required to maintain functional posture of the residual rearfoot
- The lift height underneath the heel to make up for any residual LLD in cases when calcaneal angle could not be restored to 40°
- Size of the Blue Rocker (or actual product) so the plantar surface of the prosthesis matches the rocker aspect of the footplate
- The actual shoe (preferred), or a tracing of the insole of the shoe in which the custom device will be used
**Other considerations**

**Footwear**

Footwear is the final integral component of the foot/socket/lever arm complex. To support the function of this intervention, shoes should be selected that incorporate a firm counter, with a higher counter becoming more important as the level of amputation increases. A laced shoe with a stable shank, and perhaps most importantly, a rocker toe are also features that should be specified (Figure 30). A shoe with a rocker toe will help facilitate the transition from the second to the third rocker (mid-stance to toeoff) and will produce a more fluid gait.

**Floor reaction**

As the BlueRocker is an anterior shell device, it can have influence on when the knee extension moment occurs during gait. If the device induces that knee extension influence too early in the gait cycle, it can create knee hyperextension. If that is the case, simply post the bottom of the posterior aspect of the BlueRocker footplate to delay when that moment occurs. If there is a crouch gait influence, lower the heel height to help induce more of an extension moment. It can take as little as 1/16” posting to alter the timing of the knee extension moment.

**Neuromuscular re-education**

Now that the patient has a new prosthetic environment in which to function, they will benefit from a simple series of exercises that will help them acclimate to the new device. They may need to learn how to utilize and rely on the energy reflecting properties of the BlueRocker. They may need to learn a new COG during ambulation, and also adapt to new levels of stability while walking on uneven surfaces.

If this is a relatively recent amputation, the process is usually quick and easy – minutes or hours. If the patient is coming out of long standing use of a less functional device in which much of gait was proximal compensation, the learning process may take several weeks and may necessitate professional gait training by a physical therapist.
Start with a simple baby squat maneuver (defined as flexing the knees during shoulder width stance, trunk relatively upright), to the point when the heels want to come up off the floor. Instruct the patient to do 1 set of 10 with the shoulders in-line with the hips, then 1 set of 10 with the shoulder rotated to the right, and finally one set of 10 with the shoulders rotated to the left (Figure 31). This will help the patient appreciate the floor reaction aspects of the anterior shell. Adding in the transverse plane of motion will help them adapt to walking in something other than a straight line on a flat floor.

Next instruct the patient in doing baby lunges, defined as transferring body weight to a forward foot. This should be done with both knees slightly flexed (Figure 32). Complete 1 set of 10 stepping to the lateral, 1 set of 10 stepping straight ahead, and 1 set of 10 doing a cross-step, then switch legs. This will help the patient learn the levels of stability available as he makes turns during ambulation.

Finally instruct the patient in doing hip the excursion exercise. This is especially important if the patient is coming out of long-standing use of a less functional device. Instruct the patient to stand only one or two inches away from a chair back or other such fixture or furniture. Have them barely touch the object with their hip and come back to neutral without bearing weight on that fixture (Figure 33). Start with 1 set of 10 with a slight posterior rotation, then 1 set of 10 in the straight frontal plane, and then 1 set of 10 with a slight anterior rotation of the pelvis. When the patients are confident with one or two inches of excursion, instruct them to move 3 or 4 inches away from the object and repeat the exercise. The goal should be about four inches of excursion to each side to feel totally stable in the transfer of COG at the pelvis during gait. This exercise will help the patient develop confidence in accepting the
transfer of COG at the pelvis as weight-bearing transitions from one limb to the other, thereby minimizing the amount of trunk sway during ambulation.

**Summary**

The prosthetic management of partial foot amputees is a multi-faceted task that can be daunting in its complexity. The device that will best serve the needs of the patient is one that can manage all aspects of both limb preservation and gait restoration. This paper has attempted to outline such a process in a complimentary and synergistic manner.

**About the authors**

Robert Meier, CO, BOCO, is Director of Education and Sales for Allard USA. He has over 30 years of experience in orthotics with a specialty in closed chain functional gait biomechanics. He can be reached at robert.meier@allardusa.com

Seamus Kennedy, C.Ped, MS (Eng) is President of HERSCO Orthotic Labs, Queens, NY. He specializes in functional biomechanics, and has been active in the field for over 12 years. He can be reached at seamus@hersco.com

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