RUNNING

Running is one of the most efficient ways to achieve aerobic conditioning. It can also be one of the most difficult activities for a person with lower limb amputation. Running requires foot-over-foot movement and causes musculoskeletal stress from the impact of landing. Many individuals wearing prostheses can comfortably sprint and run short distances; however, running long distances presents an entirely different situation. Long-distance running requires a high degree of personal motivation. For those with lower limb amputation, it also requires a properly designed prosthesis and a residual limb that is able to withstand the substantial forces generated by the impact of landing.

Over the past decade, the accomplishments of several runners with lower limb amputations have provided motivation and inspiration for others. Some have completed ultra-marathons, such as Terry Fox, who at age 19 logged up to 30 miles a day to make a 3,330 mile run across Canada in 1980. In 1985, Steve Fonyo, also 19, ran nearly 5,000 miles across Canada. In the same year, 21-year-old Jeff Keith ran 3,300 miles across the U.S., wearing the recently developed Seattle Foot.

Not only the young have become outstanding runners. In 1982, Bart Van Housen, at age 35, ran over 900 miles from the Oregon border to Mexico. Robert Kerrey, Congressional Medal of Honor recipient (Vietnam) and U.S. Senator from Nebraska, runs 5 miles a day. Ray Mann, a Vietnam veteran, has run a marathon (26.2 miles) in under 4 hours using the Seattle Foot.

RUNNING IS NOT FOR EVERYONE

Running is a strenuous form of exercise. It can sometimes cause debilitating problems with regard to skin, muscles, ligaments, and tendons in the legs. Therefore, running as exercise should be carefully considered by those with lower limb loss. Factors that affect the ability to run are the nature of the surgery, the level of amputation and the condition of the residual limb, the prosthetic fitting, the general state of physical fitness, and personal motivation.

It is recommended that everyone, particularly those over age 35, consult a physician before starting a running or jogging program for fitness and conditioning. Once medical approval has been obtained, individuals who have not previously exercised should proceed with moderation. Before a new prosthetic leg is built, anyone with lower limb amputation considering running should inform the prosthetist so that he or she can design it with that in mind. If running or jogging causes any pain or irritation, the prosthetist should be consulted immediately.

Most individuals will not be able to run or jog for extended distances and time without periodic irritation to the residual limb. Alternative aerobic activities may be better for those who experience persistent residual limb irritation. Activities such as walking, swimming, or bicycling are less traumatizing to the residual limb.
RUNNING SURFACE

The running surface substantially affects the ability to run. Running on grass does not cause stress to the body as much as running on a concrete or asphalt surface. For the runner with lower limb loss, however, grass may be more difficult. The surface is not always even; rocks and holes can throw a runner off balance, causing irritation to the residual limb. Running on grass also tends to dampen the push-off built into energy-storing feet. Even with these problems, some runners prefer grass because it lessens the shock to the body.

In contrast to grass, a concrete surface provides a platform for the spring in the energy-storing foot to react with greater intensity, since nothing is lost by the force absorption of the ground reaction.

Thus, a hard, even surface is often preferable to grass because it is a consistent surface, permitting the runner to land the same way each time.

Many recently constructed running tracks have tartan turf or a hard rubber surface. This may be the best type of track for disabled runners because the material is slightly forgiving, yet it has an even surface.

Treadmills provide an even surface that absorbs some of the landing impact. The treadmill is also excellent for practicing and improving the foot-over-foot running technique and for cardiovascular training.

ENERGY-STORING FOOT DESIGN

Runners with leg amputations have run for years prior to the development of energy-storing
feet. But because their prostheses provided no spring and lift, running was painful and induced great trauma to their residual limbs and throughout their bodies. Energy-storing feet provide comfort as well as improved performance. They have helped to make it possible for an athlete such as Dennis Oehler to run the 100-meter dash in 11.73 seconds at the 1988 Paralympics in Seoul, Korea, and for Jim MacLaren to complete the 1988 New York Marathon in 3 1/2 hours, the fastest recorded time for a marathon runner with an amputation.

The Seattle Foot and the Carbon Copy II Foot are energy-storing feet that are particularly well suited to running because of their responsiveness, light weight, and adaptability to many conventional prostheses. The Flex-Foot is excellent for distance running as well as sprinting. It represents the maximum in energy storage potential. The Flex-Foot is one of the lightest weight prosthetic feet available. The Springlite Foot and the Carbon Copy System III are recently developed energy-storing feet that are made of carbon fiber material.

**BELOW-KNEE PROSTHETIC ADAPTATIONS**

The weight of the entire BK running prosthesis should not exceed 3 pounds. Components fabricated from Kevlar, fiberglass, Spectralon epoxy, and acrylic resins, as well as from plastics, graphite, or titanium can provide for strong, lightweight limbs that weigh from 2 to 2 1/2 pounds. Improvements in suspension methods help lighten the sensation of weight of the prosthesis. For example, a cuff strap can be enhanced by adding a neoprene suspension sleeve over it or by adding a waistbelt. A latex rubber or neoprene sleeve by itself can also be added as an auxiliary suspension to a supracondylar prosthesis or patellar tendon-bearing (PTB)-style BK prosthesis. The 3S silicone suction socket and Icelandic Roll-on Suction Socket (IceRoss) are new methods of BK suspension which use no straps, belts, or sleeves.

To help protect the residual limb while running, a nickleplast liner with selectively placed silicone gel, a complete silicone gel liner with horsehide, injection-molded silicone liner, or the PM Liner help reduce the shear forces associated with skin breakdown. Silicone end pads also help absorb impact and prevent possible injury to the distal end of the residual limb.

Because there is great impact on the limbs as they land on the ground, weight must be distributed evenly through the socket of the artificial limb. In designing a socket for a potential runner, the use of multiple, clear diagnostic sockets and alginate impression material helps to ensure a total contact fit for even distribution of pressure. Some may find that they need to add side joints and a thigh lacer to further reduce forces on the residual limb by some transfer of weight to the thigh. This also may help prevent skin breakdown. Some runners, however, will find these additional components restrictive and cumbersome. Once the socket is constructed, the runner should exercise on it and slowly increase the running distance covered. Any problems should be resolved prior to making the finished prosthesis.

**Anterior Distal Tibia Problems**

A common problem among runners with BK amputations is excess pressure on and possible skin breakdown over the distal anterior portion of the tibia. The tibia is the larger of the two major bones
in the leg. In a person with a BK amputation, the anterior distal portion is the lower front section of the tibia in the residual limb.

Jogging is usually characterized by a gait pattern that extends the knee so that the foot lands first on the heel. However, running patterns show that people usually land on their forefoot when sprinting. The forces that control the knee from heel strike to foot flat result in the residual limb extending into the socket as the knee is flexing in order to control the prosthesis. Thus, there is greater danger of developing pressure and possible skin breakdown when landing heel first. A foot that provides plantar flexion will help control the knee and greatly lessen the forces on the anterior distal tibia. However, landing on the forefoot is usually best.

Socket Fit and Suspension. One way to help prevent skin breakdown at the tip of the tibia is to ensure a comfortably fitted and accurately contoured socket. A loose-fitting and ill-contoured socket with incorrect suspension can result in fric-
Alginate is used inside of the clear diagnostic check socket to create a total contact fitting for a below-knee residual limb.

A clear diagnostic check socket is used with atmospheric suspension.

Another way to prevent anterior distal tibia problems is by changing the materials used in the socket. A flexible inner socket material, such as stress-relieved polyethylene, can be used with rigid outer socket material, such as polypropylene. When the outer rigid socket is cut out over the distal end of the tibia, leaving the flexible insert exposed, pressure is relieved. This concept may be used for flexibility in other areas of the socket as well, so long as the socket structure is not weakened.

A prosthetic nylon sheath can be placed underneath the sock to help reduce friction. This allows the prosthetic socket to slide over the sheath rather than over the skin, which can sometimes lead to skin breakdown. Some runners use two or three sheaths at a time to help reduce shear forces on the skin and help to “wick” off perspiration. Also, runners who know that their skin breaks down in the same place each time they run should use skin care pads or Second Skin (among other products) as a preventive measure by putting them over these areas before they run.

Gait Patterns/Prosthesis Design and Alignment. Landing on the heel rather than the ball of the foot is often caused by the alignment of the artificial limb. For someone with BK amputation, a heel-toe gait is not harmful in walking, but in running or jogging it causes excessive force on the anterior distal portion of the tibia. Anterior distal tibia problems caused by a heel-toe gait can be alleviated by using a prosthetic foot that allows for easy plantar flexion. At heel strike the foot should drop quickly toward the ground. This prevents the need for knee flexion to control the leg from heel strike to foot flat. The addition of the Endolite MultiFlex Ankle or the Seattle Ankle MultiAxial Rotation (MARS) unit is excellent to accommodate the running pattern.
The Solid Ankle Cushion Heel (SACH) foot, with a soft heel cushion, is a single-axis foot that provides for plantar flexion. It was designed to help stabilize the knee and make walking smooth and natural. Unfortunately, it is not good for running since it is not energy-storing. The Flex-Foot is similar in reaction to a single-axis type of foot when the softer heel is chosen for the runner’s weight and for the distance run.

Most energy-storing feet do not have a true single-axis design, but some, when combined with additional ankle components, can provide an active form of plantar flexion. The Seattle Foot, Carbon Copy II Foot, SAFE Foot, STEN Foot, and Otto Bock Dynamic Foot are energy-storing or have dynamic elastic response and can be combined with a compatible ankle unit. The use of Endolite’s Multiflex Ankle or the MARS unit on any of these feet will enhance their multi-axis function for running. The Seattle Ankle, when added to any of these feet, also provides a degree of active plantar flexion, which helps reduce anterior distal tibial pressure. (In this case, plantar flexion is the act of lowering the foot from heel strike to foot flat.)

The DAS (Dual Ankle Spring) Foot develops its energy storage release from the compression of an anterior spring and offers ease of plantar flexion from the posterior spring compressing. The combined anterior/posterior spring also offers a multi-axis function. It is excellent for sprinting off the toe section because the keel extends to the end of the foot, thus enhancing running speed.

Because anterior distal tibial problems can occur from jogging when a person lands with an extended knee at heel strike, it is preferable to land on the ball of the prosthetic foot or on the toes (as a runner or sprinter does). Thus, many joggers naturally take on this pattern of running with knee flexion to land on the toe section as a self-protective mechanism, in order to prevent pain resulting from excess pressure on the anterior distal tibia. Although jogging with a flexed knee may not look as nice as running with long strides, it may be the only way for some individuals to run long distances without causing problems to the anterior distal tibia.

Running with the knee slightly flexed helps one land on the ball of the foot. However, if the quadriceps muscles are weak, it can be difficult to land on the ball of the foot with a flexed knee. In this case, a cuff strap that holds the knee in flexion helps maintain the leg in the desired degree of flexion. The cuff strap may be combined with a suspension sleeve for additional support. A suspension sleeve alone does not hold the leg in flexion while running, but it will be adequate for those with strong knees and quadriceps muscles. The addition of side joint and lacer may also be needed for some individuals.

Summary. Each person’s residual limb is unique and each prosthesis may require special adaptations. An artificial leg used for walking may never result in anterior distal tibia problems. The walking alignment often can also be used for running, but some individuals will require a special leg with a running alignment. Two common changes made for a running leg alignment are increased toe-out to compensate for greater internal rotation at the hip, and a longer toe lever on energy-storing feet to provide a stiffer spring rate for an increased push at toe-off. Some prosthetic legs aligned just for running force the runner to land on the ball of the foot.

Options to consider to help prevent anterior distal tibia pressure are summarized below:

1. a well-fitting BK socket/total contact/surface-bearing socket (non-prominent patellar bar, if any);
2. socks with no more than 5-ply thickness;
3. sheaths to reduce shear force;
4. an even load on both sides of the tibia on the medial flare and pre-tibial compartment along with a posterior wall high enough to prevent cantilevering;
5. a flexible socket liner and a rigid outer frame cut out over the crest of the tibia or other pressure areas;
6. full gel liner or selectively placed gel over distal tibia;
7. a prosthetic foot and ankle that will provide plantar flexion from heel strike to foot flat;
8. flexed knee gait (optional cuff suspension for landing on the forefoot);
9. preventive skin care using Spenco™ 2nd Skin™ and Spenco™ Skin Care Pads or Johnson & Johnson Bioclusive® Pads.

ABOVE-KNEE PROSTHETIC ADAPTATIONS

Two main characteristics of running that make it different from walking present a challenge for
people with AK amputation. First, the increase in velocity causes the stance phase to make up only 30 percent of the gait cycle, while the swing phase accounts for 70 percent. Second, in normal foot-over-foot running, both feet are off the ground simultaneously for a short period of time.

**Foot-Over-Foot Versus Hop-Skip Running**

Individuals with AK amputations have had great difficulty running in a normal foot-over-foot fashion because the impact at heel strike must be absorbed by knee flexion. Conventional AK prosthetic components do not provide a great deal of knee flexion. Without knee flexion, one must use a hop-skip method of running. In the hop-skip method, both legs cannot be off the ground simultaneously. A double-stance phase takes place when the sound leg makes the second hop. The extra second hop gives the time needed to get the prosthesis out in front. The hop-skip method causes the legs to be close together at heel strike, which lessens the impact when landing on the prosthesis and decreases the knee flexion moment. The hip is also in a better position to extend the residual limb to further control the tendency for increased flexion of the knee.

The hop-skip pattern was used by Terry Fox during his 1980 run across Canada to raise funds for research of cancer, the disease which caused him to lose his leg. His original idea to use a spring to absorb the shock was developed after his death.
prosthesis using the spring idea was designed to help many people with AK leg loss by alleviating ground impact and allowing for comfortable foot-over-foot running. It is called the Terry Fox Running Prosthesis, and can be combined with a conventional quadrilateral socket.\(^9\)

Impact at heel strike is alleviated by the Terry Fox Running Prosthesis through the spring shaft, which compresses and cushions the impact to the residual limb. From heel strike through mid-stance the spring is compressed to shorten the prosthesis slightly and lower the center of gravity. As the runner rolls over the toe, the spring is released, weight is taken off of it, and energy is released at toe-off, which moves the prosthesis forward into swing phase.

**Socket Design and Other Components**

Socket fit is the most critical feature of the AK prosthesis for a runner. As with socket design for BK prostheses, clear diagnostic sockets with alginate impression material helps to ensure a total contact fit for even distribution of pressure. Injection-molded silicone gel in selected locations of the socket reduces shear forces and provides additional shock absorption, particularly for the quadrilateral socket wearer.\(^10\)

Foot-over-foot running is improved through combining CAT/CAM or Narrow M/L sockets and Stance and Swing Phase knee units with energy-storing feet. Components designed for foot-over-foot running are made of lightweight plastics, graphite-epoxy composite, and titanium. A flexible brim socket adds comfort by providing a more forgiving material on heel-strike impact.

New socket designs providing ischial containment also enable foot-over-foot running. In these new designs, the ischial tuberosity is contained in the socket instead of resting on a posterior shelf as in
the quadrilateral socket. This reduces shock forces on the ischial tuberosity at heel-strike, which is particularly important since running produces ground reaction forces that amount to three to five times the body weight. A conventional prosthesis with quadrilateral socket design will not allow the individual to withstand forces so great while running.

A socket with ischial containment also provides alignment stability and control of the femur that surpasses that of the quadrilateral socket. There are several names for sockets based on these principles of design: the Narrow M/L or Normal Shape Normal Alignment (NSNA) socket, the CAT/CAM socket, and the Ischial Ramal Containment (IRC) socket, as well as several derivatives.

Hydraulic knees that feature stance and swing control, such as the Mauch SNS Knee Unit, provide the stability and knee flexion control at midstance needed by AK runners. The Mauch SNS Knee Unit is excellent for running when enhanced with the Endolite Stabilized StanceFlex (Bouncy) Knee. When these two units are combined, they provide a form of cushioning from the rubber torsional element. This reduces the forces on the residual limb and results in increased comfort, adding to the forward propulsion of the limb during the later stages of the stance phase.

There is also a need to accelerate the lower shank portion of the leg fast enough to get it out in front of the runner. A device designed for foot-over-foot running, the OKC Running System, does this. The system extends the lower portion of the leg...
The Endolite Stabilized StanceFlex (Bouncy) Knee supports weight at mid-stance for runners with single-limb soundness. Also shown is a flexible brim CAT/CAM suction socket and a Mauch Swing Phase Hydraulik Knee Unit, which is used for cadence control while running.

quickly enough to maintain the rhythm of foot-over-foot running. The system allows for hip flexion while tension is drawn on a cable which attaches to and extends the lower shank section of the AK prosthesis. When the lower portion of the leg is not extended quickly enough, a hop-skip pattern will allow the prosthetic leg to “catch up.” A constant friction knee can be used with the OKC Running System, acting as a stabilizer during the stance phase because it keeps the leg extended until toe off.

The OKC Running System is excellent for teaching people with AK amputation to run because the cable does the work for them and they can have immediate success. If desired, the system can be removed from the leg when the user learns how to run. However, many users prefer to keep it attached to the leg because it insures placement of the leg in front of them when running.

Flexible sockets, stance-controlled knees, and energy-storing feet, combined with training and practice, now enable people with AK amputation to run if they wish. However, running foot-over-foot is most common for shorter distances and limited time periods. The majority of runners still run long distances using the hop-skip step method. To date, there has not been a runner with AK amputation who has completed an ultra-marathon or cross-country event running foot-over-foot. However, it is undoubtedly only a matter of time.
The OKC Running Cable is attached to an exoskeletal prosthesis with a flexible brim CAT/CAM socket, constant friction knee, and SAFE Foot. This system allows for foot-over-foot running.

After swimming 1 mile and cycling 25 miles, Richard Hughes runs 10 kilometers to finish a triathlon.
Roger Charter, thought to be the first person with bilateral above-knee amputation to run foot-over-foot, is shown running with the energy-storing Sabolich Feet and CustomFlex Sockets™.

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