CHEMISTRY Helps Athlete Keep Moving

By Stuart Mason Dambrot

Chandler Smith (right), who has been wearing a prosthetic leg and foot since he was 18 months old, has played soccer, golf, basketball, and, currently, lacrosse.

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CHANDLER SMITH was born without a right leg due to a rare nonhereditary birth defect. His condition, called proximal femoral focal deficiency, resulted in a bone deficiency that prevented him from developing a leg bone called the tibia, deformed his right foot, and caused another leg bone (the femur) to be underdeveloped.

When he was just 18 months old, Chandler became a patient at Shriners Hospitals for Children® – Los Angeles, Calif. After consulting with physicians, occupational and physical therapists, and social workers, his parents agreed that having his leg amputated and receiving a prosthetic leg and foot would help Chandler avoid lifelong deformity and give him the best possible quality of life.

After a successful operation, Chandler received his first above-the-knee titanium prosthetic leg—and because he was growing, he had to be fitted for new ones almost every year. The prosthetic leg and foot are separate, and different prosthetic feet were designed for specific purposes—for example, running versus hiking—to be attached to the prosthetic leg. Despite this apparent limitation, Chandler says he was born to be an athlete—and he is true to his word. In addition to wrestling, he has played soccer, golf, basketball, and, currently, lacrosse. "My parents encouraged me to play sports and always supported me," Chandler says. "I started playing sports at a young age and never let anything hold me back."

Adjusting to a prosthetic leg and foot

Chandler's doctor, Phoebe Scott-Wyard, a pediatric physiatrist (physical medicine and rehabilitation physician treating children and young adults), notes that walking and running with his prosthetic leg has been challenging for Chandler. He was accustomed to using a prosthetic leg with a knee joint for everyday use (similar to the one shown in Fig. 1b), but the new prosthetic leg (similar to the one shown in Fig. 1a) did not have a knee—so Chandler had to learn how to move with a prosthetic leg made without a knee. When he was running, he had to learn how to move his leg so his foot traces a circle, while the top of his leg remains fixed.

The other major challenge is financial. Prosthetic legs are often cost-prohibitive, with an average cost of \$5,000–\$15,000—but until he was 18 years of age, Chandler received a prosthetic leg and prosthetic running foot every year, along with all care and services, which are provided at Shriners regardless of a patient's family's ability to pay. Shriners could no longer offer Chandler free prosthetics and related services once he turned 18. As a result, Chandler's parents initiated a crowdfunding Web site to help raise the funds for new prosthetics. A crowdfunding site raises small amounts of money from many people, primarily via an Internet campaign.

When Chandler received his new prosthetic leg, he was concerned there might be problems with the way it fits, because the remainder of his right leg—called a stump or residual limb—might respond to the prosthetic in ways that may affect how it fits. He engaged in regular training at his physical therapist's office—which involved work on parallel bars, stairs, ramps, and level ground.

The prosthetic leg's fit was fine-tuned by making small adjustments in the region where the leg contacts the residual limb, helping Chandler to learn how to accommodate his new leg. Now, Chandler says, he is excited about his most recent prosthetic leg, which fit well, adding, "I never felt so comfortable running in my life."

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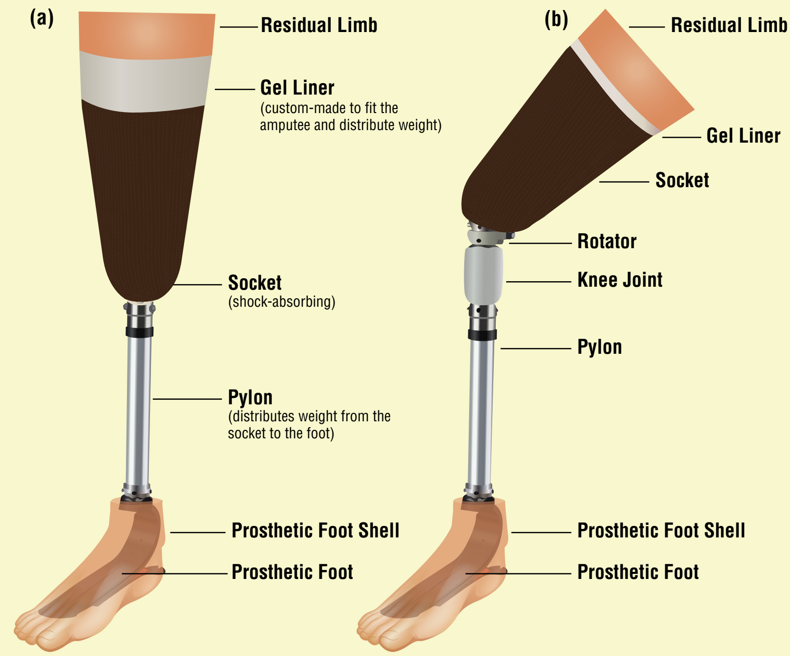

Figure 1. Prosthetic legs come with or without a knee. (a) In a prosthetic leg without a knee, the pylon (lower part of the prosthetic) and the socket (which replaces the lower part of the thigh) are directly attached to each other. (b) In a prosthetic leg with a knee, a knee joint and a rotator are present between the pylon and the socket, allowing the prosthetic leg to bend.

In fact, Chandler's new prosthetic leg and foot are working so well that he would like to become a personal trainer, own a gym, and compete in triathlons and Spartan races. "My new prosthetics enable me to run better at longer distances without pain," he says.

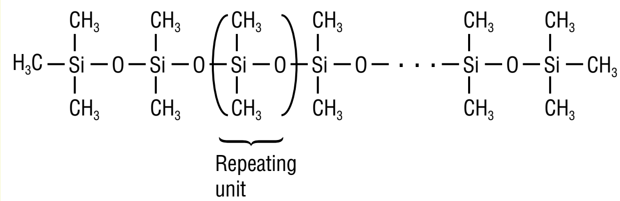

Figure 2. Chemical structure of a silicone elastomer

"I never felt so comfortable running in my life."

Chandler Smith

Prosthetic leg

To make sure the prosthetic leg lasts at least 6 months, it needs to fit the shape of the leg comfortably, not irritate the skin, and be sturdy enough to be worn all day in a rigid socket and washed every night. Prosthetic designer Denis Jordan, who works for Shriners Hospitals, addressed these issues with an innovative socket design and silicone liner. The liner, which is part of Chandler's prosthetic leg, is a protective covering that fits over the residual limb and between the residual limb and the socket (Fig. 1). Liners are generally softer and more comfortable than the socket, but they are not rigid enough to support the amputee's weight without the support of the socket.

These properties can be achieved thanks to rubber-like materials called silicone elastomers—materials with elastic properties that are resistant to chemical attack and are unaffected by temperature changes and can exist as liquid, gel, rubber, and hard plastic.

Silicone elastomers are made of long molecules, each consisting of repeating units composed of one silicon atom, two carbon atoms, and one oxygen atom (Fig. 2). Each molecule consists of a backbone of alternating silicon and oxygen atoms, and the remaining two bonds of the silicon atoms occur with organic groups, such as methyl groups ($–CH_3$).

The prosthetic leg needs to be compatible with living tissue, or biocompatible—that is, it should not release chemicals that are toxic to the body. The material of choice to prevent this from happening is titanium, a lustrous silver-colored transition metal with high strength and high resistance to corrosion in seawater. More important, titanium's surface properties

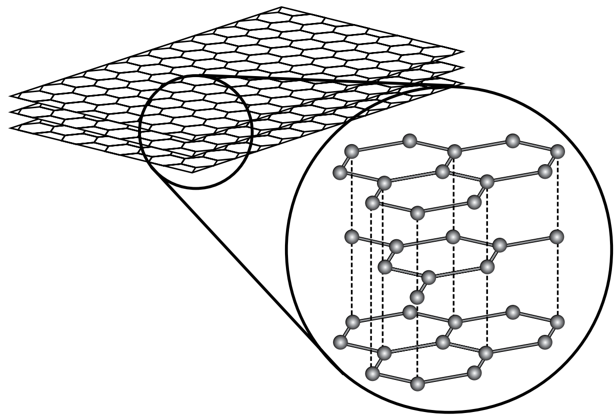

Figure 3. A cross section of a carbon fiber with (inset) a close up of the atomic structure of the planes of carbon atoms that make up the carbon fiber

make it resistant to corrosion from bodily fluids because of the protective titanium dioxide (TiO_2) film that forms naturally in the presence of oxygen.

Prosthetic foot

Chandler's prosthetic foot was manufactured from carbon fibers, which are very thin filaments of carbon that are about 5–10 micrometers in diameter. Carbon fibers are very light, are 10 times stronger than titanium, and do not expand very much when temperature increases. These properties make Chandler's prosthetic foot feel light yet stiff, and the foot does not

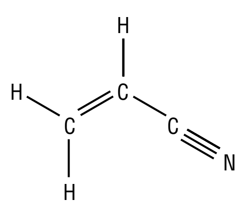

Figure 4. Chemical structure of acrylonitrile

stretch when Chandler runs or when it is too hot or too cold outside.

Each carbon fiber is composed of sheets of carbon atoms in which the atoms are bonded covalently to form hexagons (Fig. 3). The planes are stacked onto one another, and bonding among carbon atoms between planes occurs through weak intermolecular attractions, which allow the planes to slide past each other.

How are these long sheets of carbon produced? Not by linking carbon atoms, as one might assume, but by combining small molecules called acrylonitrile (CH_2CHCN) (Fig. 4).

These molecules can react with each other to form a long molecule called polyacrylonitrile. This is another example of a polymer which, in this case, consists of CH_2CHCN units (Fig. 5). The polyacrylonitrile molecules are then heated in air to 200 °C–300 °C, so the cyano side groups (–CN) form cyclic rings with one another. Further heating causes the rings to lose hydrogen from the carbon atoms.

Then, by slowly applying heat between 400 °C and 600 °C, adjacent polymers bind together (Fig. 6). By repeating this process, a sheet of graphite (with nitrogen molecules on its sides) is produced.

Several thousand carbon fibers are twisted together to form a yarn, which may be used by itself or woven into a fabric. The yarn or fabric is combined with a substance called epoxy and wound or molded into shape to form a light yet strong material called a carbon fiber-reinforced composite—the material used in Chandler's prosthetic leg.

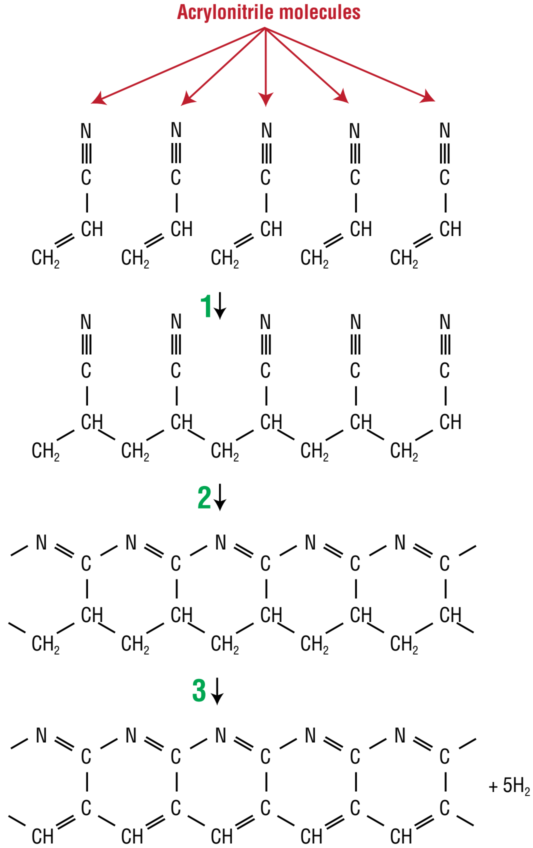

Figure 5. The synthesis of carbon fibers begins with the polymerization of acrylonitrile molecules to form polyacrylonitrile (step 1, in green). The polyacrylonitrile molecules are heated to 200 °C–300 °C for 30–120 minutes, which causes them to rearrange their atomic bonding pattern (steps 2 and 3, in green). The polyacrylonitrile molecules are then heated to a temperature of 400 °C–600 °C for several minutes in a furnace, which causes them to fuse together (Fig. 6).

Chandler Smith was a goalie for his high school team, the Chaparral (Temecula, Calif.) JV Lacrosse team.

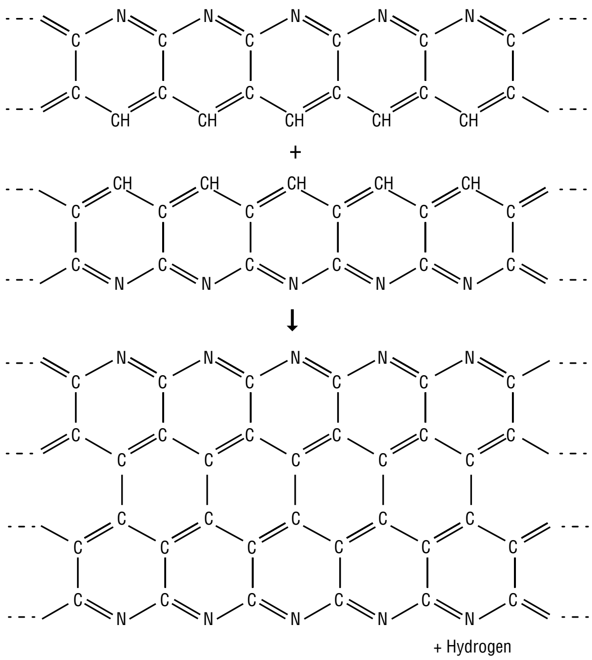

Figure 6. By slowly applying heat at a temperature between 400 °C and 600 °C, adjacent chains of polyacrylonitrile bind together to form a sheet of hexagonal carbon structures.

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"I started playing sports at a young age and never let anything hold me back."

Chandler Smith

Figure 7. The OPRA Implant System is an example of an osseointegrated prosthetic leg that is attached directly to the bone by inserting a threaded titanium implant into the bone marrow at the amputated end of the residual limb.

New technologies afoot

Prosthetics have steadily improved over the years to make them more comfortable and flexible to the wearer and make them last longer. A technique gaining traction as a mainstream prosthetic treatment is "osseointegration," which refers to the direct connection between living bone and the surface of an artificial implant. The word derives from the Greek *osteon,* bone, and the Latin *integrare,* to make whole.

This technique is the result of a chance discovery made more than 50 years ago by Swedish Professor Per-Ingvar Brånemark. Brånemark was experimenting with titanium implants in rabbit bone when he noticed that the bone had completely integrated with the implant. He and his team found that titanium eyepieces, placed into the lower leg bones of rabbits could not be removed from the bones after a period of healing.

With osseointegration, the prosthetic leg is attached directly to the bone by inserting a threaded titanium implant—referred to as a bolt or fixture—into the bone marrow at the amputated end of the residual limb (Fig. 7). A few months after the bolt is inserted into the bone marrow, the bolt integrates into the bone—a natural process that encourages the growth of new bone and blood vessels. Once the bolt is integrated, a titanium connector (called an abutment) is attached to the bolt and made to pass through the soft tissue and skin.

The prosthetic leg can then be easily attached to and directly removed from the abutment without having to fit into a socket. This eliminates pain caused by the residual limb growing or shrinking within the socket or by friction and irritation, if the prosthetic limb, socket, and liner are not kept clean and dry.

An osseointegrated prosthetic leg offers many benefits, including increased range of motion, elimination of pressure, sores, and pain caused by the socket, improved sensory feedback from skin and muscle, and better walking ability. An osseointegrated prosthetic leg was not appropriate for Chandler, because titanium is more than twice as rigid as bone, so the bone into which the threaded titanium bolt is implanted can fracture from the high forces from a sports activity. Also, the bolt can become loose from a sports activity, so running and jumping are not recommended and are even prohibited, in some cases.

Prosthetic limbs have had a tremendously positive effect on Chandler and many others. Titanium, carbon fiber, elastomers, and other materials can be fashioned into a comfortable, biocompatible prosthetic leg and foot, enabling Chandler to move more naturally and fulfill his dreams in the exciting and challenging world of sports. The success of these prosthetics also makes us wonder what their future may hold—and, in some cases, those possibilities are already a reality. CM

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