



Engineering the Skeleton

By: **Trudy E. Bell** ©2024 Trudy E. Bell

Each year, over a million people worldwide become bionic when major joints of their skeletons are replaced with prosthetic implants. Here's a brief sketch of some engineering backstory.

Above Image Credit: Terry Dagradi (Yale University). See sidebar on page 10 for more information.

When my left hip finally failed in late June 2022, the sustained pain was the worst in my life. Even with a walker, I could hardly journey the length of my apartment without gasping. I was already maxed out on Meloxicam, and extra strength Tylenol offered zero relief. I sent my wonderful daughter out to purchase a wheelchair, and was fortunate that a cancellation let me move an appointment with an orthopedic surgeon from mid-July to the next day. After the agony of X-rays and a consultation, when he informed me that the next available surgery date would be forever away on August 1, I asked: “How am I supposed to survive until then? And after five weeks in a wheelchair, won’t it become inoperable?” “You’re a long way from that,” he replied reassuringly, but demurred prescribing stronger pain meds.

The hip failure—possibly due to the last of the cushioning cartilage being worn away, leaving the joint bone-on-bone—couldn’t have come at a worse time: I was in the middle of packing to move and both apartments were a jumble of boxes, many heavy with books.

I had been praying that the hip could last into September when the move would have been complete, but the joint’s degradation had accelerated in the final few weeks. (Surgeon: “That happens sometimes.”)

The hip had begun to have issues in 2011, when I first noticed an aching limitation in the range of motion when doing a sideways knee-lifting exercise known as the “fire hydrant.” Over the years, I obtained periodic relief from several rounds of physical therapy and walking up and down hills. And there was the nonsteroidal anti-inflammatory drug (NSAID) Meloxicam and the analgesic Tylenol. But X-rays and an MRI of my hip and lumbar region revealed “advanced severe degenerative osteoarthritis,” the most common form of arthritis, which is inescapably progressive. Slowly, the hip’s range of motion became increasingly limited and stiff. Eventually, it even felt as if the hip would almost give way under my weight from one step to the next. The long-term trend line was headed in the wrong direction.

As August 1 approached, I became frankly terrified. First, I realized I had to trust this surgeon, who looked like a boy, to cut out and replace a key part of my skeleton. Second, I feared that post-surgical pain would exceed even the appetite-sapping suffering I was already enduring. But the status quo (daily pain level averaging 8 to 9.5, maybe 7 on a good day, with no end in sight) was a nightmare prospect. I had no choice but to power through the surgery.

IF YOU LIVE THROUGH IT...

Three hours after the surgery, when I woke from the general anesthetic, several hospital aides assisted me to stand with full weight-bearing. My first thought: “These post-operative pain meds are very good.” Blessedly, blissfully, I felt no pain. Indeed, after the anesthetic wore off, I realized, “oh, this post-surgical pain is entirely manageable”—bone-on-bone had been 100 times worse. (Surgeon: “A lot of people say that.”) Second, I realized “this hip isn’t going anywhere!” It was rock solid.

“Don’t worry about breaking the implant,” explained my gifted surgeon—Dr. Christopher Bechtel (pronounced “BETCH-el”), then of University Hospitals—when he visited my hospital room that afternoon. “It’s the strongest thing in your body. Your original hip joint was very severely damaged. The ball had basically disintegrated and the socket was resting directly on the arthritis.”

Within days, using a walker, I was walking the length of the corridor of a residential rehab facility. (Daughter Roxana: “This is the first time I’ve had hope.”) By Halloween, I was walking without a cane, without pain, and without restrictions, and by New Year’s was back to hiking forest trails.

Although millions of people had previously gone through similar surgery (and worldwide a million more each year receive new hips¹), from my individual patient’s personal viewpoint, it felt nothing short of a medical miracle. Moreover, my curiosity was sparked: joint replacements had to have an under-appreciated materials science and structural engineering backstory. My journalist’s motto: If you live through it, write about it.

ANATOMY 101

First, some essential medical vocabulary: the femur (thigh bone) is the longest and strongest bone in the body. It (and the body’s other long bones) is made up of two kinds of bone: cortical bone (the strong, dense, and compact outer layer that makes up 80 percent of the skeleton) and trabecular or cancellous bone (porous honeycomb-like inner bone found at the ends of the long bones and in the vertebrae). Inside the femur is a long cavity called the medullary canal, which houses the body’s stores of bone marrow (which contains stem cells that produce blood cells and other cells essential to the immune system).

At the top of the femur is the nearly spherical femoral head that serves as the “ball” in a hip joint. It is covered with tough, slippery cartilage, and it articulates (moves) within the smooth cartilage surface of the acetabulum (pronounced “ass-say-TAB-u-lum”) or “cup” or “socket” of the pelvis [Fig. 1a]. In a healthy hip joint, there is a slight space between the two cartilage surfaces, which is filled with synovial fluid—a viscous fluid that lubricates and reduces wear on the joint.² The cartilage and synovial fluid together act as a shock absorber that cushions the repeated impacts from walking or running. The hip joint is held together by fibrous ligaments; it is articulated by muscles attached to the bones by tendons.

A functional hip joint, whether natural or prosthetic, must meet demanding engineering requirements. A “standard walking pace causes approximately five times one’s body weight to be loaded on the hip...; going up or down stairs is associated with a more than sevenfold increase in effective body weight...³ For athletes—think gymnasts or figure skaters or tennis players—fast leaps, twists, and turns can drive the effective loads far higher. A prosthetic hip joint must robustly resist fatigue for millions of cycles of compressive loading and release from muscles and tendons. It also must mimic articular cartilage in reducing friction under load and distributing stresses at the hip to resist wear from repeated movement of the femoral head within the acetabulum (the body still produces synovial fluid after a hip joint replacement).

In a diseased hip like mine, however, the space between the ball and socket had narrowed, depriving the joint of synovial fluid, the cartilage on both the femoral head and inside the acetabulum had mostly worn away, and osteoarthritic bone spurs had grown, limiting range of movement [Fig. 1b].

The idea of surgically replacing a natural hip joint with a prosthesis (“total hip arthroplasty” in medical lingo) is several centuries old, but early materials tried, such as wood, were neither strong enough nor biocompatible (that is, made of a material that the body would not reject)⁴.

Figure 1a: Healthy hip joint.
Credit: American Academy of Orthopedic Surgeons.

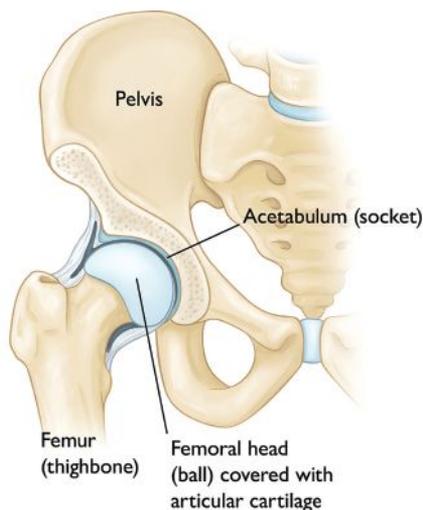
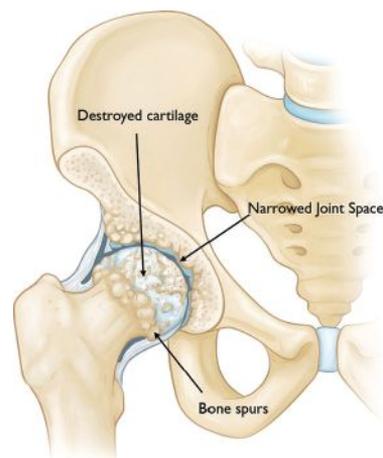


Figure 1b: Diseased hip joint.
Credit: American Academy of Orthopedic Surgeons.



The first ball-and-socket hip prosthetic implant, made of ivory and fixed in place with nickel-plated screws, was by German surgeon Themistocles Glück in 1890; later researchers tried all manner of other materials. But the acknowledged “father of modern arthroplasty” was Sir John Charnley in England, who revolutionized hip implants in the 1960s, producing the first successful low-friction, high-load-bearing, biocompatible implants with decent longevity (a decade or more), having a stem inserted into the top few inches of the femoral (medullary) canal and fixed in place with bone cement.^{3,5}

THE SOCKET

In answer to my query for details about the hip joint implant I received, surgeon Bechtel responded through his assistant Lisa Brenot:

The manufacturer of her components was DePuy [DePuy Synthes, a subsidiary of Johnson & Johnson]. She has a Pinnacle acetabular component that has a porous metal coating on the backside of the shell that is osteoconductive and allows for her bone to grow onto the surface of the shell and provide a biologic fixation. The inner liner is ALTRX highly crosslinked polyethylene.⁶

In 1962, Charnley first used an acetabular cup made of ultrahigh molecular weight polyethylene (UHMWPE) as the bearing surface of his hip prosthesis, introducing the use of high-density polyethylene as a low-friction-bearing material. Conventional polyethylene (PE) is sterilized using gamma radiation in air. That produces crosslinking of chemical bonds between individual long

polymer chains to produce a three-dimensional network, giving the PE greater mechanical strength—a good thing. But such irradiation also releases free radicals that oxidize in air, which made the PE more brittle and less resistant to wear—a bad thing, because the resulting UHMWPE wear debris could (and did) cause osteolysis (bone degeneration) and eventual failure of the implant in some early patients.

Over the decades, much research was devoted to improving wear resistance while eliminating the oxidation, resulting in the development of “highly cross-linked UHMWPE,” abbreviated XLPE. In outline (regardless of manufacturers’ individual variations), cross-linking is achieved by using gamma radiation or electron beam radiation; the polymer is then heated to near its melting temperature (137°C) to eliminate free radicals. Finally, it is sterilized in the absence of air. In clinical use, XLPE has demonstrated a dramatically lower rate of wear and osteolysis.⁷ ALTRX is a third-generation material introduced by DePuy in 2007.⁸

THE STEM

Dr. Bechtel continued:

The femoral stem is a CORAIL (French) stem. It is primarily made of titanium but it is coated in hydroxyapatite that is a known growth factor that stimulates her own bone to grow onto the stem along the length of the stem inside the femoral [medullary] canal.

In the early 1960s, the metal of choice for the femoral stem was stainless steel, but its wear resistance turned out to be poor. Other steel alloys were tried with

greater or lesser success, with a cobalt-chromium-molybdenum steel alloy proving to have good wear resistance. But it was also stiff, stiffer than cortical bone. Bone is somewhat flexible, and there was a poor match between the implant’s rigidity and the bone’s elasticity, resulting in bone resorption from “stress shielding.”

Bone requires stress to strengthen or maintain strength (hence the importance of weight-bearing exercise); without stress, it begins to atrophy. The early steel hip implants did not sufficiently transfer stress from the weight of the upper body to the femur. But titanium alloys were more flexible and had a lower mismatch with the elasticity of bone, reducing or eliminating stress shielding.

Hydroxyapatite is a naturally occurring mineral form of calcium that makes up more than half of human bones and teeth; it is often called “bone mineral.” Hydroxyapatite in various forms, whether of biologic or synthetic origin, is used in dentistry and in orthopedic applications to encourage bone regeneration around and through metal and/or ceramic implants.⁹

Bone cement for the femoral stem of hip implants, however, turned out to be somewhat problematic. Its success depended greatly on the skill of the individual surgeon: if not properly packed, the cement might not adequately penetrate the bone bed, so an implant was at risk of loosening. Moreover, microscopic particles of the cement were sometimes found in other cells, causing inflammation.

HIGH-TECH BANDAGES

The bandage that covered my direct anterior approach incision after hip joint replacement surgery looked like nothing so much as a foot-long strip of duct tape under a wider and longer piece of Saran Wrap. But both the shiny gray bandage and its waterproof transparent wrap (actually a single unit) were softer and more flexible than either actual duct tape or sandwich wrap would have been. The materials also adhered amazingly well, not lifting at the

corners even in the shower—yet when a nurse removed them seven days after the surgery, both materials came away from my skin easily with no pulling of tender tissues. Moreover, aside from looking purple and a bit lumpy, the newly healed 3-inch incision was completely clean with zero sign of inflammation. It never gave me a moment’s trouble. What kind of waterproof yet breathable dressing could be left in place for a week with no changing, have

such a remarkable adhesive, and promote infection-free healing?

According to Dr. Bechtel:

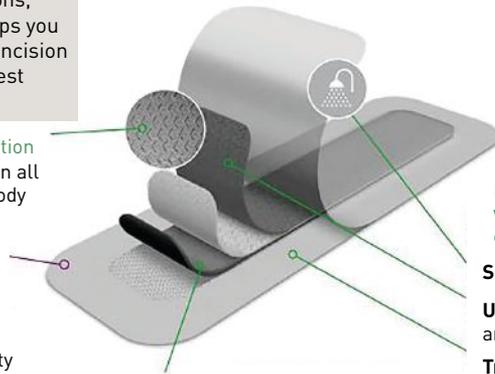
“We use dissolvable sutures to close the different layers of the tissues (muscle/deep, subcutaneous, skin) followed by skin glue over the incision. The bandage is a silver impregnated, waterproof bandage (Mepilex Ag) that elutes very small levels of silver that has known antibacterial properties. It was first used in the military for soldiers that were

Specifically designed for incisions, Mepilex Border Post-Op Ag helps you balance the many demands of incision management and deliver the best possible care.

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Safetec technology adheres gently, maintaining skin integrity



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Figure 2 : Safetac is a silicone adhesive of the Miplex Ag dressing, manufactured by Mölnlycke Health Care LLC. Read more in the sidebar at the bottom of pages 8-9.

High FHC which may support longer wear times and low frequency as compared to conventional dressings

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Thus, in the 1970s, others began trying and using uncemented designs and “intensive broaching of the femoral canal.”⁵ In plain English, that means drilling out part of the interior of the thigh bone to be slightly smaller than the implant, and then hammering the implant’s slightly larger tapered femoral stem into a snug press-fit. (I, pre-surgery: “I hope I’m out cold when all this machining and pounding are going on.” Bechtel: “You will be.”)

THE BALL

Dr. Bechtel further explained about my implant:

Lastly, she has a BIOLOX ceramic femoral head. This is a highly polished, hard and durable ceramic that has excellent wear properties when combined with the highly crosslinked polyethylene liner (0.1mm/yr linear wear of the polyethylene liner).

Since the 1970s, alumina ceramics have been used for the femoral head in total hip arthroplasty. Alumina ceramics are biocompatible, have high wear

resistance, and are chemically durable. However, early first-generation alumina ceramics were brittle and suffered a dismaying incidence of fracture. Improved manufacturing processes to decrease porosity and grain size and increase toughness reduced fracture rates and made ceramics more feasible. In the late 1980s, European researchers introduced zirconia femoral heads, which had greater bending strength and crack-resistant toughness. But manufacturing issues led to a major recall of zirconia prosthetics.

Since then, the ceramic of choice (which I received) has been zirconia-toughened alumina (ZTA), which combines the hardness of alumina with the tough crack resistance of zirconia. CeramTec first commercialized ZTA around 2000 under the trade name of BIOLOX Delta.¹⁰ Other materials have also been introduced for medical use more recently, such as silicon nitride, a tough and high-strength non-oxide ceramic with half a century of use in bearings and turbine blades.⁸

PROSTHETIC ENGINEERING

What recent engineering developments seem promising for further improving the functionality of prosthetic hip joints? Research continues into biomaterials with better biomechanical properties (including new metals, ceramics, composites, and shape-memory metals or polymers). One tantalizing engineering goal is “infinite” prosthesis life, to minimize the risk of younger and more active patients outliving their replacement hip joints.¹⁰

One big research area is personalized implants for patients with non-standard anatomy (perhaps resulting from bone defects or from congenital disorders). Such one-of-a-kind prosthetics could be constructed through additive manufacturing (also known as 3D printing).¹¹ Additive manufacturing could also enable the production of porous femoral stems whose porosity varies along the length of the stem for an even better match with the elasticity of bone.¹² Moreover, surgical robots as surgeons’ assistants seem to excel in precise positioning of customized

injured on the battlefield. They would be able to apply the bandage to any combat wounds after bleeding was controlled and it would protect the wounds from infection. It was adapted to be a common surgical wound dressing that is combined with a waterproof adhesive that can stay in place for up to a week.”

The remarkable silicone adhesive of the Miplex Ag dressing, manufactured by Mölnlycke Health

Care LLC, is called Safetac; it was specifically designed to conform to the skin without sticking to a moist wound or incision, so wounds can heal undisturbed.¹⁷ See Figure 2 Silver-impregnated dressings significantly reduce the incidence of infection not only of the superficial incision, but also of more serious deep infection of the joint implant itself. Such deep prosthetic joint infection (PJI) is a potentially

catastrophic (even fatal) complication that is a cause of implant failure after surgery, especially if caused by antibiotic-resistant organisms. “Superficial wound infections have been demonstrated to be a risk factor for deep prosthetic infection,” one research group stated. Thus, “...minimizing the risk of superficial wound complications is likely a major step toward lessening the risk of subsequent PJI.”¹⁸

–T.E.B.

'HIP' HISTORY

An entire museum exhibition on the innovation and evolution of hip joint replacement surgery? Who knew? Indeed, an extensive collection of historic artificial hip joint implants and other artifacts was assembled and put on display for three months in 2022 in the rotunda at Yale University's Harvey Cushing/John Jay Whitney Medical Library in New Haven, Connecticut.

Moreover, highlights from the artifacts of the new Keggi–Rubin Implant Collection have been beautifully photographed (see page 6) and the images presented in a comprehensive permanent online exhibition recounting their fascinating history (beginning at <https://onlineexhibits.library.yale.edu/s/hipreplacement/page/introduction>).

The exhibition's scope and purpose are aptly summarized in its introduction:

The displayed implants trace the trials, innovations, successes, and failures of hip replacement surgery over time, providing insight into the dynamic world of surgical history. By archiving and studying these implants, one can witness the remarkable changes that have resulted from design, engineering, biomaterials, manufacturing, and technological advances over nearly a century. The evolution of total hip replacement has been possible thanks to the timeless contributions and collaborations of many dedicated surgeons, researchers, engineers, industry experts, and manufacturers over the past 70 years.

The YouTube video of the 1-hour dedication ceremony on March 18, 2022, also provides some background on how the remarkable collection and the exhibition came to be. Well worth visiting. –T.E.B.

implants within patients. There has even been experimentation with “smart” implants that are electronically instrumented to give early warning of potential loosening and possible failure of the prosthetic hip joint.¹³

The annual number of prosthetic hip replacements is projected only to increase in number through time because of the world's aging human population.¹⁴ And the lifetime of prosthetic hip joints today averages a good 25 to 30 years. The durability of the prosthetic hips plus the development of minimally invasive surgical techniques have expanded the viable range of potential recipients to include younger and more active individuals.¹⁵ (P.S. Some surgical veterinarians even insert hip joint replacements to treat hip dysplasia in larger dogs!¹⁶)

Moreover, hips are by no means the only human joints replaced. Knees are even more commonly replaced. Less commonly, patients have had shoulder joints or elbow joints replaced. A growing number of individuals have had two or more joint replacements. I even personally know a woman whose entire lower jaw is of titanium (an arduous travail entailing multiple surgeries over six years, necessitated by a dental implant gone horribly wrong)—but you wouldn't know it to look at her.

Let's hear it for prosthetic engineering.



Figure 3: X-ray of the author's titanium-alloy prosthetic left hip joint as it looked in August 2023, one year after her total hip arthroplasty. (The dim circle at the far right is a calibration marker ball to help with measurements on the X-ray.) Credit: University Hospitals

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