



# **BIOTRIBOLOGY: The Tribology**

# of Living Tissues

Science continues its pursuit of wear reduction on the most advanced of machines — the human body

by Anne Jacobson



CONTINUED ON PAGE 34



## BIOTRIBOLOGY: The study of friction, lubrication and wear in biological systems, specifically articular joints.

**A**s in man-made machines, excessive wear and tear of moving parts can cause grave breakdowns in the human body. When artificial materials such as polyethylene or titanium perform poorly in the real world of bone, muscle and blood, a special subset of tribologists are summoned. These specialists in biological friction and lubrication—called biotribolo-

gy of moving tissues,” says Myron Spector, professor of orthopedic surgery at Harvard Medical School. “In the human body many tissues move in relation to one another, and the body has to allow for that movement or the tissue will split and break down.”

### MAKING HIP REPLACEMENTS LAST

Artificial hips are widely considered the most successful advance in orthopedic surgery in the last 100 years. With its high success rate, hip replacement surgery offers people with diseased joints not only freedom from pain but also the chance to walk, run or even dance again. An estimated 300,000 people in the United States undergo hip-replacement procedure each year.

Still, the success is incomplete. Based on the wear characteristics of their component materials, artificial hips should last a patient’s lifetime. But in reality these devices last only 12 to 15 years in the human body. Replacing them means another major surgery for the patient.

Today’s most common artificial hip joint consists of a cobalt-chrome alloy ball that fits into a socket made from ultra-high molecular weight polyethylene. The ball is anchored to the femur and the socket to the pelvic bone with bone cement. The movement of the ball wears into the socket—a full, fat centimeter thick—an average of only one-tenth of a millimeter per year. At that rate, it should take 100 years for the device to wear out.

Yet that seemingly negligible amount of wear wreaks havoc on the body. With each step taken by a person with an artificial hip, the slight friction of the metallic ball against the polyethylene socket grinds off an estimated 74,000 to 150,000 sub-micrometer sized polyethylene particles. Taking a million steps per year, the typical person’s body must confront trillions of these particles accumulating in the joints.

The body is ill equipped to clear these artificial debris. Swelling and osteolysis—a foreign body reaction in the joint that dis-

gists—are helping medical researchers understand wear-related breakdowns and create treatments that get the body up and running again.

With 206 bones in the adult human body, powered by about 600 muscles, there is much to understand and much that can go wrong, tribologically speaking. In addition to bones and muscle, the body relies on many other moving parts: the beating heart, chewing teeth and blinking eyes. The body also produces its own unique lubricants—tears, saliva and synovial joint fluid—which biotribologists must understand as completely as their counterparts in machine labs grasp the properties of oil and synthetic lubricants.

“From a scientific viewpoint, there are many interesting questions about the tribol-

Photo courtesy of Peterson Tribology Laboratory

A hip simulation machine shown with its dedicated computer system, one of four such machines in the Peterson Tribology Laboratory at Loma Linda University Medical Center. The blue console contains the hydraulic pump to drive the load-profiles and a DC-motor to drive the kinematic chain. Dr. Ian Clarke (pictured here) is pointing to one of the 12 sensors monitoring the dynamic “walking” loads on the hip joint (femoral ball mounted vertically underneath). The 12 plexiglass chambers contain the mating polyethylene cups immersed in a biological lubricant (bovine serum).

solves the bone around the implant—commonly occur. When the bone dissolves and weakens, the implant loosens, functions improperly and must be replaced.

## SOLVING THE WEAR PROBLEM

In tribology laboratories at academic institutions and orthopedic companies around the world, researchers are setting their sights on the holy grail of joint replacements—an implant that lasts 50 years. Most of the potential solutions involve new materials or combinations of materials with improved wear characteristics. One such approach is a more wear-resistant socket made of “cross-linked” polyethylene.

The first highly cross-linked polyethylene bearings were used in Japan by Dr. Hironobu Oonishi in the 1970s. However, it took many years before it was realized that such cross-linking reduced the formation of wear debris in the patient’s hip joint. In the mid 1990s cross-linking was still a controversial topic in the U.S. Wear machines with linear kinematics were predicting that non-cross-linked polyethylene was the optimal choice, though simulator studies with multi-directional kinematics predicted the opposite was true.

“Cross-linked polyethylene is one of the most important recent developments in the field of hip replacement,” says STLE member Thierry Blanchet, an associate engineering professor at the Rensselaer Polytechnic Institute in Troy, N.Y. “It’s a big success story.”

Ultra-high molecular weight polyethylene consists of a long backbone of carbon atoms with hydrogen atoms bonded along its length. Irradiation knocks off the hydrogen atoms, exposing the underlying carbon to free-ranging oxygen atoms. It also forms crosslinks and these crosslinks are a more beneficial effect than the detrimental effect of oxidation. In a process known as scission, the oxygen reacts with and severs the molecule’s carbon backbone. Scission causes the polyethylene to weaken and wear more rapidly.

Heating the polyethylene and giving it higher amounts of radiation for a longer time in an oxygen-free environment induces the exposed carbon atoms to cross-link.

In laboratory tests, cross-linked polyethylene wears so minimally that it is difficult to detect and measure. “We know wear occurs, but we are still working on quantifying it,” says Blanchet. Now that most of the orthopedic implant manufacturers offer hip joints made with cross-linked polyethylene, the goal is to determine how the joints perform clinically. “It’s somewhat of a waiting game,” added Blanchet.

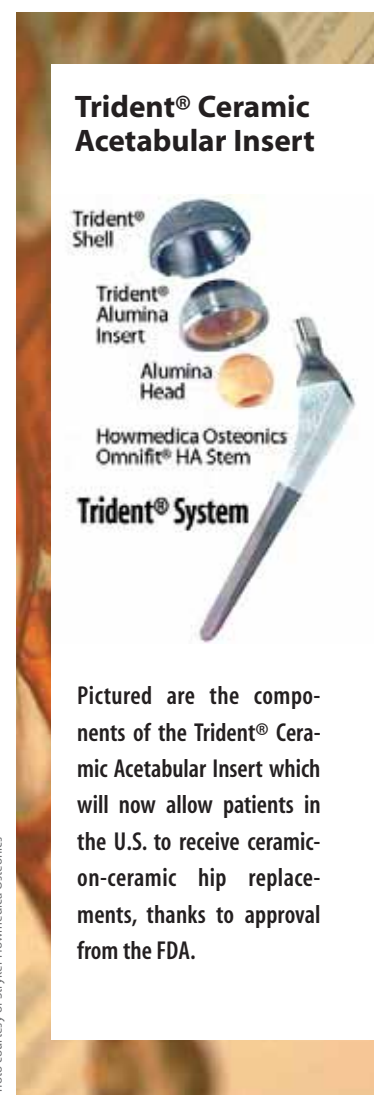
Academic and industry researchers are also experimenting with artificial hips consisting of a cobalt-chrome alloy ball and socket (metal-on-metal) or an alumina ceramic ball and socket (ceramic-on-ceramic). At the Peterson Tribology Laboratory, part of the Loma Linda University Medical Center in California, four simulators can test as many as 45 hip joints simultaneously. Running for several months or even a year, these simulators must perform 10 to 20 million walking cycles to reproduce 10 or more years of natural wear. Tests at the Peterson lab have focused not only on cross-linked polyethylene but also on metal-on-metal and ceramic-on-ceramic artificial hips.

A significant challenge facing biotribologists is finding artificial material that can co-exist with the body’s natural tissues and lubricants. “A real hip joint is lubricated by synovial fluid—syrupy, gummy stuff that nourishes the cartilage,” says STLE member Dr. Ian C. Clarke, director of orthopedic research at the Peterson laboratory. “Synovial fluid was not designed to lubricate metal or ceramic.”

Biotribologists are finding success with one new material, however. Stryker Howmedica Osteonics, a collaborator with the Peterson Tribology Laboratory at LLUMC, was recently awarded approval from the FDA for its ceramic-on-ceramic hip replacement product, the Trident® Ceramic Acetabular Insert.

“The device performed three orders of magnitude better than metal-on-polyethylene, two orders of magnitude better than metal-on-cross-linked polyethylene, and one order of magnitude better than metal-on-metal in in-vitro tests using hip joint simulators,” says Dr. Aiguo Wang, director of the tribology department at Stryker.

**An estimated 300,000 people in the United States undergo hip-replacement procedure each year.**



CONTINUED ON PAGE 36



Some metal-on-metal implants are also in use, and tribology labs around the world continue to test other material combinations, such as metal-on-ceramic, ceramic-on-polyethylene and ceramic-on-metal.

## KEEPING BLOOD FLOWING

For a person suffering from heart failure and waiting for a transplant, a mechanical blood pump called a left ventricular assist device (LVAD) can mean the difference between life and death. LVADs do not replace the heart but instead help the heart do its job. One end of the pump attaches to the left ventricle, the main pumping chamber of the heart. The other end attaches to the aorta, the body's main artery. In some patients, LVADs improve blood flow so significantly that a transplant is no longer necessary.

Current versions of these devices last only two or three years, however, because the lubricant used on their tiny bearings separates and stops working, according to Victor L. Poirier, chief technology advisor at the Thoratec Corp. Thoratec's LVAD, the HeartMate I, has been implanted in more than 2,000 patients worldwide.

"You lubricate the device before you install it, but after that you can't touch it. You can't change the lubricant or add more," says Poirier. And those millimeter-sized steel bearings need to be well lubricated. The pump starts and stops with each heartbeat—about 75 times a minute or nearly 40 million times a year. "That's a tough job on a bearing," adds Poirier.

Thoratec is trying two approaches to the problem. A second-generation LVAD, the HeartMate II, uses an axial-flow blood pump with blood-immersed bearings. With this device, blood becomes the lubricant. The bearings are coated with a textured sur-

face that, when it comes into contact with blood, creates a biocompatible lining similar to the inner surface of arteries and veins. The HeartMate II is undergoing trials in humans, and Poirier hopes the device will be shown to last five or 10 years.

Thoratec's HeartMate III eliminates bearings altogether. The device uses a centrifugal-flow rotary pump with a magnetically levitated impeller.

"In this system, no parts are touching," says Poirier. "The magnetic field is the bearing." The HeartMate III is still in laboratory development, but Thoratec plans to submit an application to the FDA to test this pump in people, with the hope it will last significantly longer than HeartMate II.

## OCULAR TRIBOLOGY: IN THE BLINK OF AN EYE

Some biotribologists have focused their efforts on the human eye and the problems that can occur when this delicate organ is not properly lubricated by tears.

"With the popularity of contact lens wear and the ever-increasing popularity of refractive surgery, understanding the mechanism of action of eye lubricants becomes highly important," says Dr. Frank J. Holly, president of the Dry Eye Institute in Lubbock, Texas. "Eyelid motion in blinking requires an effective lubrication system to prevent damage to the sensitive ocular surfaces."

Holly and other ocular tribologists study tears and the mechanics of blinking in order to help create better artificial tears to treat dry-eye syndrome. Caused by a decline in the quality or quantity of one's tears, the syndrome affects 10 million people in the United States.

Tears are a complex combination of substances that form three layers on the eye. The highly viscous outer layer is composed chiefly of fatty molecules called lipids and is very thin (0.1 micrometer). The watery, low-viscosity middle layer, called the aqueous tear layer, is about 10 micrometers thick. The innermost layer is composed of viscous mucus that helps the tear film stick to the surface of the eye.

Most researchers believe that the outer lipid layer is the chief lubricant during

The HeartMate left ventricular assist device (LVAD) has become a useful tool in helping the heart function properly.

Photo courtesy of Thoratec Corp.

blinking. But Holly argues that when the eye closes during a blink, the outer lipid layer is compressed and swept away by the moving eyelid so that the lubricating layer between the lid and the eye is actually the watery tear layer, bounded on both sides by mucus. The mechanism of eye lubrication, therefore, is hydrodynamic.

Holly adds that the current practice of using high viscosity lubricants or ointments to treat eye problems may actually interfere with lid lubrication and tear formation. Lower viscosity lubricants would work better, he believes.

"The present elasto-viscous approach, while it works, is not the best," says Holly, describing the eye drops and lubricants commonly used today. "These things are unfortunately not clear to most physiologists or physicians." Holly and other ocular tribologists continue to seek better artificial lubricants, taking cues from the delicate architecture of human tear layers.

### DENTAL TRIBOLOGY: SEEKING THE GOLD (OR ENAMEL) STANDARD

Artificial teeth are commonly made from acrylic, porcelain or gold, but dental prosthetics makers are still searching for materials with improved wear characteristics. Ideally, the new material should approach the wear rate of human enamel. In laboratories in the United States, China and Japan researchers are conducting wear-resistance studies on a variety of new materials.

Titanium, both in its pure form and as an alloy, has emerged as a leading candidate. During the last decade pure titanium has been increasingly used to make artificial teeth for both fixed and removable partial dentures. But while highly biocompatible and corrosion resistant, pure titanium also has poor frictional wear characteristics. Clinicians have noticed that titanium teeth tend to deform, come unglued from the denture base and discolor.

Some have tried titanium alloys to solve this problem, but scientists don't know much about the wear characteristics of these alloys. Researchers at the Baylor College of Dentistry in Dallas and the Tsurumi University School of Dental Medicine in

Yokohama, Japan, recently collaborated to test the wear characteristics of five titanium alloys against pure titanium and a control of gold alloy teeth. Their experiment provides an example of the experimental strategies dental tribologists use and the challenges they face.

After casting five pairs of upper and lower teeth in each type of material, the researchers placed each pair in a wear-testing apparatus that simulates chewing. The upper and lower teeth were mounted two millimeters apart, and the machine applied a 5-kg vertical load from the upper tooth

**Whether working on artificial joints, blood pumps, eyes or teeth, biotribologists from diverse fields are united by a common challenge.**

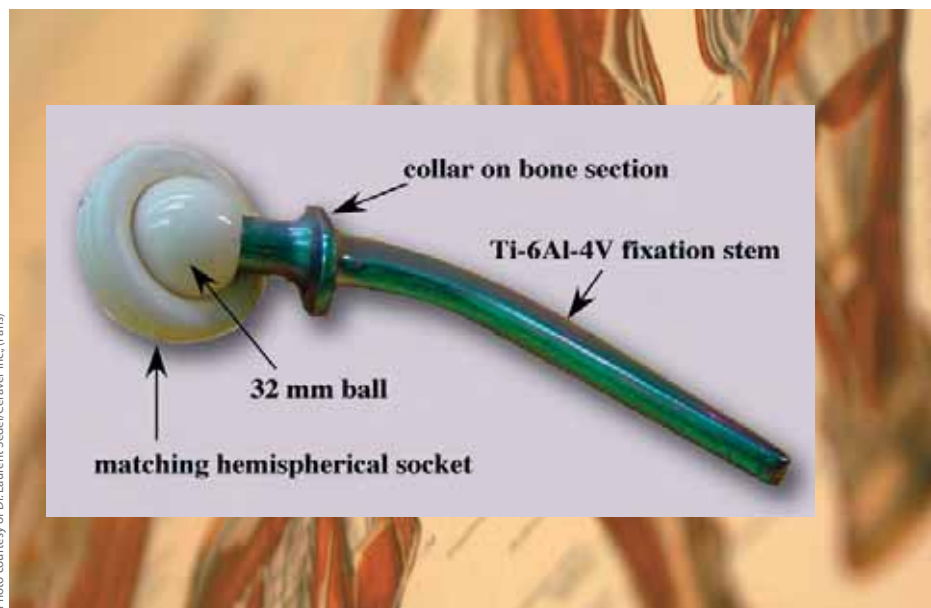


Photo courtesy of Dr. Laurent Sedel/Ceraver Inc., (Paris)

onto the lower. As the upper tooth contacted the lower, the machine also shifted the lower tooth horizontally, causing a sliding motion from cusp to cusp. The wear testing machine performed this action 60 times per minute for a total of 50,000 cycles, spraying the artificial teeth continuously with water to simulate the moisture in the mouth.

Researchers then assessed wear by measuring volume loss of the artificial teeth and by examining them under an optical and scanning electron microscope. Two of the titanium alloys performed significantly worse than pure titanium, two performed slightly better, and one about the same. None—not even pure titanium—performed better than the gold alloy used as a control.

**This total-hip joint prosthesis retrieved from a patient after 18 years of use shows negligible wear of the ceramic bearings. The 32-mm diameter ball is aluminum, as is its mating acetabular cup. The anchoring stem is made of titanium alloy and is for fixation with polymethylacrylate bone-cement inside the bone of the upper leg (femur). These implants were sent courtesy by Dr. Sedel to Dr. Clarke for analysis.**

CONTINUED ON PAGE 38

With 206 bones in the adult human body, powered by about 600 muscles, there is much to understand and much that can go wrong, tribologically speaking. In addition to bones and muscle, the body relies on many other moving parts: the beating heart, chewing teeth and blinking eyes.

"The results of this study showed that gold alloy has the best wear resistance," the researchers concluded in a recent paper in the *Journal of Prosthodontics*. "Keeping in mind that the mechanical properties of many dental casting gold alloys are similar to those of pure titanium, these results certainly indicate the complexity of wear testing."

### HOPES FOR BETTER TESTS

Dr. Clarke of the Peterson lab echoes the sentiment expressed by the dental researchers—that accurate wear testing in biotribology is difficult. High on his wish list for the future of biotribology is equipment and materials to mimic the human body more accurately. For example, because of the scarcity of natural synovial joint fluid, laboratory hip joint simulators must use bovine serum for lubricant.

"We're studying a lubrication problem, but we can't get enough of the lubricant. We can't test what you are actually walking on," says Clarke. "Just to start my machines, I need six liters of lubricant. If I took all the synovial fluid out of your body it would

amount to about one cubic centimeter—and you would be left with painful joints. I doubt you would volunteer for that."

Clarke's problem may be helped somewhat by Myron Spector's forward-looking research at Harvard Medical School. Spector and colleagues are trying to clarify the mechanical properties of synovial joint fluid and how those properties vary among individuals. This line of research might one day lead to a synthetic lubricant for human joints, although such a possibility is still a long way off. Such a synthetic lubricant would presumably improve wear testing.

Whether working on artificial joints, blood pumps, eyes or teeth, biotribologists from diverse fields are united by a common challenge. Under the conditions that prevail in today's biotribology labs, it is "easy to be wrong and hard to be predictive and correct," adds Clarke. "Unfortunately, it seemed like we had been working in the dark much of the time in the 1980s and 1990s."

According to Clarke, there has been a concerted effort worldwide to develop a more systematic approach to such biolubrication problems. These include detailed micro-wear studies on bearings retrieved from patients along with separation and characterization of wear debris for comparison with the various laboratory models

Many laboratory studies now routinely use specially roughened bearings as a more aggressive wear model. Some centers such as the Peterson laboratory have now added "unstable" or micro-separation modes to their simulator test protocols as worst-case scenarios to simulate the more at-risk patients.

In these various ways we are beginning to see much more clearly the cause and effect relationships that may be working in the tribology of the human hip joint. <<

Dental tribologists have discovered titanium alloys have increasingly been used to make artificial teeth for use in dentures. Though, recent studies have shown much is not known about the wear characteristics of these alloys.

*Anne Jacobson is a science and medical writer based in Silver Spring, Md. She also contributes to Computing in Science and Engineering, CBS HealthWatch and WebMD. She can be reached at [ajacobson@nasw.org](mailto:ajacobson@nasw.org).*