



## The Science of Friction

Ease-of-use, wear and patient comfort are just some of the concerns about devices designed to be used in the body. Reducing friction through improved materials, lubricated coatings and surface treatment can tackle all of these issues, as Julia S Rasor of the Rasor Consulting Group explains.

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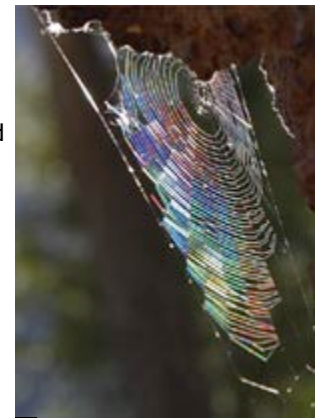
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The design of medical devices that contact the body (surface devices, external communicating devices, and implantable devices) as well as devices that contact other devices or have parts that come in contact with each other, must involve the consideration and measurement of friction, or the relative slipping motion of a material over another material. The science of friction, lubrication and wear is called tribology.

Reducing friction minimises wear and, in some cases, inflammation or toxicity that can result from wear debris. Friction reduction also minimises insertion forces, such as for catheters, and maximises patient comfort and the machineability of medical devices.

Examples of medical devices for which slip is important are prostheses; feeding tubes; wound drains; endotracheal tubes; trochars; catheters; dilators; guide wires; angioplasty balloons; vascular, biliary and urethral stents; patches; filters; hypodermic or suture needles; and electrical pacemaker leads. Some of the methods used to increase slip/decrease friction are choice of materials, lubrication, surface treatment and coatings.

**"The science of friction, lubrication and wear is called tribology."**



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Silk-based biomaterials harness natural properties.

### Measuring slip

**Friction.** Friction is not a fundamental force so it must be found empirically. An instrument that measures friction on a surface, a tribometer, is composed of a ball sliding on the reference surface that provides a relative friction value. The measure of sliding resistance of a material over another material, or the coefficient of friction  $\mu$ , is defined by the equation  $\mu = F/N$  where  $F$  is the tangential force required to produce sliding between two solid surfaces and  $N$  is the normal force between the surfaces. This coefficient depends on the materials used.

The friction created between device and tissue, for example the catheter-wall friction of intracoronary ultrasonic imaging catheters, has coefficient values of approximately 0.04 for low catheter introduction force, and 0.2 for high. The slipperiest solid known (called BAM for boron, aluminium and magnesium), discovered in 1999, has an approximate coefficient of friction of 0.02, about half that of Teflon®.

**"Reducing friction minimises wear"**

Biomaterials science has progressed in reducing the coefficient of friction, however, biological systems remain far superior, as the coefficient of friction for articular cartilage on articular cartilage is 0.0025.

**Wear.** Tribological interaction of a solid surface's

and, in some cases, inflammation or toxicity that can result from wear debris."

exposed face with interfacing materials and environment may result in loss of material from the surface, or wear. Tribotesters are used to perform tests and simulations of wear, friction and lubrication. Orthopaedic implant manufacturers have spent considerable sums of money to develop tribotesters that accurately reproduce the motions and forces that occur in human hip joints so that they can perform accelerated wear tests of their products.

A measurement of the severity of wear is the wear coefficient  $k$ , which is a dimensionless constant described in the Archard equation  $k = V/[ND/H]$  where  $V$  is the total volume of wear debris produced per unit distance moved,  $N$  is the total normal load,  $D$  is the sliding distance, and  $H$  is the material hardness. The wear coefficient for materials used in medical devices are shown in Table 1.

**Asperity and fretting.** The unevenness or roughness of a surface is its asperity, and asperities are slight projections or rough, sharp, or rugged outgrowths of a surface. Fretting refers to wear damage at the asperities of contact surfaces. The amplitude of the relative sliding motion is often in the order from micrometers to millimeters, but can be as low as 3-4nm. The contact movement causes mechanical wear and material transfer at the surface, often followed by oxidation of the debris and the freshly exposed surface. The oxidised debris can further act as an abrasive.

The friction and wear in hip prostheses result in very small wear particles that are released to the surrounding joint cavity, initiating an aggressive inflammatory response. The fundamental way to prevent fretting is to design for no relative motion of the surfaces at the contact. Surface finish plays an important role as fretting normally occurs by the contact at the asperities of the mating surfaces. Lubricants are often effective in mitigation of fretting by reducing friction and inhibiting oxidation.

### Improving slip - choice of materials

**Man-made.** It is conventional to classify the materials of engineering into six broad classes: metals, ceramics, glasses, polymers, elastomers and composites. A good example of evolution of materials selection in order to minimise friction and wear is total artificial hip arthroplasty. The earliest design, around 1958, was a polymer-on-polymer materials combination consisting of a PTFE or Teflon acetabular element articulating against a PTFE femoral component. Debris from PTFE wear led to inflammation and pain.

Among the most successful material pairings is the ceramic-on-polymer joint. It has however, a limited lifetime of 15-20 years due to polymer wear particles. Since the 1960s, polymer-on-metal joints using ultra high molecular weight polyethylene (UHMWPE) polymer have been the material of choice for hip, knee and spine arthroplasty.

Metal-on-metal (MOM) or ceramic-on-ceramic (COC) articulations are also used. MOM joints are usually made from alloys of cobalt, chromium, and molybdenum (Co-Cr-Mo). These alloys have excellent hardness and strength, but may raise questions about long-term metal-ion exposure from wear particles.

The advent of new ceramics (primarily alumina and aluminazirconia composites) having excellent hardness, and thus high wear and scratch resistance, allowed for improved COC designs. Ceramic particles are seen as biologically inert, so COC joints do not have a biological effect. COC implants can fracture, however, because



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A tribometer measures friction between two surface materials.

"Biomaterials science has progressed in reducing the coefficient of friction, however, biological systems remain far superior."

ceramics are brittle materials.

**Non-man-made.** Silk, a naturally occurring polymer, has centuries of use in medicine as sutures. Domestic silkworm silk is composed of a filament core protein, termed fibroin, and a glue-like coating consisting of sericin proteins. It is biocompatible once the immunogenic sericin coating is removed. To date fibroin from the silkworm has been the dominant source for the silk-based biomaterials studied, as silkworms have undergone 5,000 years of domestication.

Conversely, spiders have not been domesticated for large-scale or even industrial applications since farming the spiders is not commercially viable due to their highly territorial and cannibalistic nature. However, spider silks have a similar structure to silkworm silk but do not have a sericin coating, making them slippery and more desirable as a biomaterial.

Silk fibroin from spiders, and those formed via genetic engineering or the modification of native silk fibroin sequence chemistries, in various formats (films, fibres, nets, meshes, membranes, yarns and sponges) has been shown to support stem cell adhesion, proliferation, and differentiation in vitro and promote tissue repair in vivo.

"The friction and wear in hip prostheses result in very small wear particles that are released to the surrounding joint cavity, initiating an inflammatory response."

In particular, stem cell-based tissue engineering using 3D silk fibroin scaffolds has expanded the use of silk-based biomaterials as promising scaffolds for engineering a range of skeletal tissues like bone, ligament and cartilage, as well as connective tissues like skin. Silks are stable at physiological temperatures, flexible, and resist tensile and compressive forces, and spider dragline silk is five times tougher than steel wire and two to three times tougher than synthetic fibres like Nylon or Kevlar. It is also antimicrobial, hypoallergenic and biodegradable.

Nexia Biotechnologies Inc of Montréal is using transgenic goats to secrete the proteins into milk, and plans to use its spider-silk product, BioSteel® Medical, for wound closure, vascular grafts, haemostatic devices and matrices for drug release. Spider drag-line silk was introduced for the first time in 2006 as a new biomaterial for microelectromechanical systems (MEMS). A spin-coated thin film was successfully formed onto a silicon substrate.

**Surface treatments**

**Electropolishing.** Electropolishing, also referred to as electrochemical polishing, is a process that removes material from a metallic workpiece. It is used to polish, passivate and deburr metal parts. It is often described as the reverse of electroplating. It differs from anodising in that the purpose of anodising is to grow a thick protective oxide layer on the surface of a material (usually aluminium) rather than polish.

**Electroplating.** Electroplating is primarily used for depositing a layer of material to bestow a desired property (such as abrasion and wear resistance, corrosion protection, lubricity and aesthetic qualities) to a surface that otherwise lacks that property.

**Ion implantation.** In artificial joints, it is desirable to have surfaces resistant to chemical corrosion and wear due to friction. The surface modification caused by ion implantation includes a surface compression which prevents crack propagation and an alloying of the surface making it more chemically resistant to corrosion. Ion beam-assisted deposition is also used in coating a titanium base alloy component of a heart valve with a strongly adhered coating of diamond-like carbon.

MATERIALS		WEAR COEFFICIENT (K)
SEVERE WEAR		
Si3N4	Si3N4	1.5x10 <sup>-4</sup>
AlN	AlN	1.5x10 <sup>-4</sup>
SiC	SiC	1.5x10 <sup>-4</sup>
SiC	SiC	1.5x10 <sup>-4</sup>
SiC	SiC	1.5x10 <sup>-4</sup>
SiC	SiC	1.5x10 <sup>-4</sup>
SiC	SiC	1.5x10 <sup>-4</sup>
SiC	SiC	1.5x10 <sup>-4</sup>
SiC	SiC	1.5x10 <sup>-4</sup>
MILD WEAR		1.5x10 <sup>-4</sup>

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 Table 1. Wear coefficients (k) of materials engineered for use in medical devices.

**Irradiation.** Highly cross-linked UHMWPE materials have rapidly become the standard of care for total hip replacements. These new materials are cross-linked with gamma or electron beam radiation and then thermally processed to improve oxidation resistance. Five-year clinical data demonstrate superiority relative to conventional UHMWPE.

**Glow discharge.** Radio-frequency glow discharge surface treatment of the silicone rubber covering of electrical heart pacemaker leads improves their slip properties.

### Lubrication

Lubricants are placed between two surfaces to lessen the coefficient of friction. Examples of lubricants used in medical devices include: silicone; colloidal solution of water and lecithin used during the manufacture of intravenous catheters; polyphenyl ethers as electrical connector lubricants; and the solid lubricants molybdenum disulphide, PTFE, powdered graphite and boron nitride for flexible endoscopes. Nature solves its lubrication problems with water as a base stock and biomolecules as additives.

Similar to the natural joint, the artificial joint is lubricated by a body fluid (synovia) that contains biological macromolecules. However, the surface of cartilage in natural joints, has completely different properties than an implant polymer surface. Cartilage is hydrophilic, whereas the polymer (polyethylene) surface is very hydrophobic, which has a drastic effect on the way these macromolecules from the synovia can adsorb onto the surface.

Current research focus is to understand and enhance the boundary lubrication properties of synovial macromolecules on polymer surfaces with the aim of modifying the polymer surface to increase hydrophilicity.

### Coating

Desirable properties of coatings for medical devices are: low coefficient of friction; durable; lubricious; biostable; non-leaching; biocompatible; controlled thickness; coating and bonding ability; ease of application; thin; conformal; micro-encapsulation capability; barrier properties including chemical, moisture, and electrical; and economical.

Examples of coatings used in medical devices are: electroless nickel/phosphorous plating solution coupled with a mixture of non-stick plastic coating material, for example PTFE, which includes islands of metallic material or metallic material embedded therein to assist in electrical conductivity for use on electrically activated instruments; hydrogels for use on catheters that are utilised to deliver a stent, graft or vena cava filter, or balloon catheters; and silicone, or hydrophilic polymers.

A polymer brush coating consists of a surface with a concentrated coating of polymer chains, each with one of its ends bound to the surface. It serves as an effective lubricant, producing friction coefficients as low as 0.001 or less.

Tribologists have progressed and achieved slipping success using a multitude of technologies for many medical devices. However, biological systems in nature still remain far superior.

*Research material has been referenced in this text. For full details please contact the editor, [andrewtunncliffe@spgmedia.com](mailto:andrewtunncliffe@spgmedia.com).*

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