ADVANCEMENTS IN MEMS AND NEMS FROM BIO-TRIBOLOGICAL PERSPECTIVE

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ABSTRACT

Biotribology is a field dedicated to the understanding of many sliding and frictional interfaces in living tissue. The field gained popularity in the 1990´s due to miniaturization of electromechanical components which prompted issues related to grinding and wear at smaller scales. This is, since MEMs and NEMS have gained control over medication, biotechnology, optics, hardware, and avionics and, due to the scale, continuum mechanics cannot accurately describe such nanoscale phenomena.

MEMs and NEMS are increasingly used in industrial and defense applications. In chemistry these devices allow smaller reagent volumes and faster reaction times, and the simultaneous execution of multiple types of analyses. In biotechnology, these are used to examine DNA or proteins in order to detect ailments or find new medications. They are also known as DNA arrays, and they're capable of identifying thousands of genes at once. In the pharmaceutical industry, they serve as drug delivery systems. Indeed there are several applications for such kind of devices and in order to increase the number of fields of application, it is necessary to overcome several tribological challenges.

Thus, this review focuses on tribology in Bio MEMS/NEMS, its applications, advancements and challenges since device miniaturization is one of the frontier technologies of the 21st century.

Keywords: MEMS; NEMS; Bio-tribology; Nanoscale

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Received: Jun 28, 2021; **Accepted:** Aug 12, 2021; **Published:** Sep 30, 2021

Citation: Molino J, Arauz B, Reginensi D, Nieto C, de Tristan S, et al. (2021) Advancements in MEMs and NEMs from a Bio-tribological Perspective. J Nanomed Nanotech Nanomat 2:113.

INTRODUCTION

Tribology is the field of exploration managing grating, wear, and interaction between surfaces in relative motion [1,2]. It is crucial to develop systems prompting less wear via improved erosion conditions and consequently extend the life cycle of machines and gear, lower fabrication costs, less energy use, and diminished carbon footprint. This literature review provides an overview of some current applications and future possibilities of such in biology. Here we present a few examples of all-around well-developed biological systems demonstrating the possibilities science biology can offer engineers. Tribology is pertinent in fields as diverse as mechanical design, creation innovation, the automotive industry, (aero)space innovation, building innovation, energy supply, gadgets designing, clinical innovation, and exactness designing. Due to miniaturization, the area to volume ratio in devices is increasing. Micro tribology and nanotribology are therefore particularly significant [3,4]. Indeed, this is complex technology; macrotribological relations cannot be simply downsized to the nanometer scale. The "smooth surface" or the Hertzian contact utilized in the Hertz model does not apply to this scale. Therefore, distinct research in this field is a discreet discipline [5].

There are a wide range of examples from nature that are applicable in nanotribology. Evolution provides creative innovations such as developing new materials for reducing friction. For instance, Velcro is the result of biomimetic design. George de Mestral developed the innovation after observing how the tiny naturally snared spines of a plant adhered to his dog's coat. Today, Velcro is a multi-million-dollar business [6,7].

Scherge and Gorb present a comprehensive summary of "natural tribological systems" [8]. They analyze frameworks with diminished erosion, like joints, and frameworks with expanded contacts, such as

interlocking gadgets in bird quills through snares or the gecko's connection stack. They also present frameworks with expanded grip, such as the sticking pads of tree frogs, and frameworks with anti-sticking mechanisms, like those found in self-cleaning surfaces of plants and creatures, such as the dung beetle. Another pertinent example is the lotus' water-repelling properties; its mechanism could be mimicked in several applications ranging from self-cleaning paint for vehicles to anti-sticking coatings for within containers [8,9].

With miniaturization the efficiency of the systems increases. Micro electromechanical devices and nanoelectromechanical devices (MEMS/NEMS) are gaining popularity due to increased energy efficiency and high reaction speeds. Thus an understanding adhesion and stiction among molecular layers (either biological or non-biological) is crucial for designing better devices and pushing the boundaries of biomedical man made systems further.

Nanoelectromechanical systems (MEMS/NEMS) refer to a nanoscopic device with a length of less than 100 nm that combines electrical and mechanical devices. Biotechnological or biological procedures normally include groups of cells or molecules, whereas nanotechnological approaches work on a single molecule. Natural nanostructures can be found in many biological systems, including viruses, membranes, and protein complexes. They may, however, be examined in the same way as non-biological structures, and their properties can be used in nanostructure design and development [10,11].

Systems combining biological and chemical components with physical devices and electrodes (Bio-MEMS/NEMS) are increasingly being recognized as having enormous potential for application, not only in the development of analytical and monitoring devices but also in the development of molecular-scale bioreactors. Biotechnological operations typically involve populations of cells or molecules (or, in certain situations, individual cells or organelles), whereas nanotechnological procedures manipulate individual molecules. Proteins are huge molecules made up of many amino acid chains. All eight necessary amino acids are found in complete proteins. Proteins are an essential component of all living organisms. They are required for the proper functioning of every cell and undertake a wide range of tasks, including catalyzing metabolic activities, DNA replication, and stimulus response [12]. Their principal role, on the other hand, is to heal wounds, fight infection, and build muscle. The wide range of protein activities available for biosensor applications allows for a wide range of actions to be conducted at the nanoscale [6,11,13-18].

Silicon is a popular substrate for micro-implants, but it can potentially interfere negatively with the human immune system, while proteins are essential in bio/nanotechnology, like coatings on various engineering surfaces are critical in multiple biomedical applications, including micro-implants, biosensors, and therapeutics. As a result, protein coatings are used as passivation layers on silicon-based surfaces to imitate a biological surface, ensuring that these implants are compatible with the body and prevent rejection. Because of their functional specificity, proteins are also used in BioMEMS/NEMS [19-21].

The vast range of protein activities offers a rich supply of operations that can be performed at the nanoscale for biosensor applications. Antibodies that bind to protein antigens have a high affinity. For example, pathogens (disease-causing agents such as viruses or bacteria) produce antigens that can be identified when attached to a particular antibody on the biosensor [22]. Proteins with complex binding activity used in laboratory assays may be redesigned for use as sensing elements in BioMEMS/NEMS *in vivo*. Proteins with epitope-specific antigen-binding properties are helpful in therapeutics. The protein-substrate adhesion influences the reliability of an application. Furthermore, the proteins on the biosensor surface should have a high wear resistance when in direct contact with the tissue in vivo environments. [8,16,23]. On the other hand, about biosensors, entered on a field-effect transistor, this is an example of a microarray biosensor (FET). FETs are sensitive to the electrical field produced by the charge on the gate insulator's surface. A protein (receptor layer) whose cognate is the analyte (e.g., virus or bacteria) that is supposed to be sensed replaces the gate metal electrode of a metal oxide semiconductor field-effect transistor (MOSFET) in this sensor [24]. Proteins may have anywhere from one to twenty-five (positive or negative) charges per molecule. The electrical field changes as the receptor layer binds to the analyte, causing a difference in the effective charge. The presence of analyte can be identified if the electrical field changes, causing a measurable shift in current flow through the system. The biosensor's reliability is influenced by the adhesion between the protein layer and the silica substrate. [19,25].

Biosensors embedded in the external environment, such as tissues and fluids, and any relative motion of the sensor surface respecting the external environment can cause surface damage. When an embedded biosystem surface comes into contact with living tissue, a diagram of the generating points of friction and wear is seen. In these applications, the biosensor surface's friction, wear, and adhesion are essential [26]. Chemical and biochemical tests, biosensors in medical diagnostics (e.g., DNA, RNA, proteins, cells, blood pressure and assays, and bacterial pathogens or toxin identification), tissue engineering and implantable pharmaceutical drug delivery are all applications for BioMEMS/NEM [25], [27-31].

They are increasingly used in industrial and defense applications. Liquids and gases are dealt with by biosensors, also known as biochips. Micro and nanofluidics are used in a wide range of biosensors. Micro and nanofluidic devices allow smaller reagent

volumes and faster reaction times, and the simultaneous execution of multiple types of analyses [1]. Another type of biosensor is micro and nanoarrays. They can be used thousands of times to perform a single type of analysis. For example, a chip embedded on the disk with micro and nanofluidic technology, known as lab-on-a-CD, can test thousands of biological samples quickly and automatically [32]. An example of such a device is a silicon-based disposable blood-pressure sensor chip. This monitor checks blood sugar every 10 minutes by detecting glucose through the skin without drawing blood [27,33], as well as the rapid serological tests of COVID-19, which do not detect the virus directly but rather identify the IgM and IgG antibodies present in the blood or plasma [34].

Other forms of biochips include micro and nanoarrays. They are utilized in biotechnology research to examine DNA or proteins in order to detect ailments or find new medications. They are also known as DNA arrays, and they're capable of identifying thousands of genes at once. They contain a microarray of silicon nanowires with a diameter of a few nanometers that can selectively bind and detect a single biological molecule like DNA or protein. To detect the tiny electrical charge created by such binding, they use nanoelectronics or a microarray of carbon nanotubes to detect glucose electrically [8, 35].

BioMEMS/NEMS are also produced for nonintrusive medical procedures, including endoscopies, laser angioplasty, and micro-medical procedures. Indeed, the characteristics of a BioMEMS/NEMS are given by the application. The BioMEMS/NEMS (nanoparticles) surface loaded with the drug must be site-explicit functionalize for drug delivery systems [13,24,27,36].

For drug delivery applications, extended delivery can be attained when the surface can be modified at the nanopore level and load it with drugs. Some BioMEMS/NEMS are employed for sequencing single atoms of DNA; in some cases, cell carbon nanotubes are used for spinal line fix, spinal combination gadgets, organ development, and development of tissues utilizing nanofibers [25].

In general, through nanotechnology, we can take segments from cells and partially make them function outside the organism. Soong et al. built one of the first bio-nanomechanical gadgets: various organic sub-atomic engines on nickel posts (height 200 nm, width80 nm) [37]. The engine moved due to the expansion of adenosine triphosphate, a high-energy phosphate particle used to store and deliver energy for work inside living organisms. The machine has a scale close to a single molecule. Wear in such gadgets would affect their operation and wreck it. Tribological considerations in the design are crucial, particularly for human-made nanomachinery used in physiological conditions [24].

One significant obstacle in current human-made micro and nanomachines is their tendency to aggregate. Biological nanomachines have finely tailored functional surfaces, so they only aggregate under abnormal situations. The aggregation of misfolded proteins with exposed hydrophobic groups is an example of this. Even in these circumstances, structures have developed to repair the machinery, like molecular chaperones, which are proteins that help other proteins fold properly [38,39].

In cases where the relevant parameter is severe, it may be the finest technique to study building concepts about optimization to distinct parameters. Many organisms thrive in severe environments, such as those involving temperature, pH, and other factors. In one well-known case, an extremophile-inspired technique resulted in a Nobel Prize, a large sum of money, and the foundation for the polymerase chain reaction, or PCR, a standard tool for rapidly reproducing DNA [1,2].

The great efficiency of biological systems reveals the actual limits that can be reached. It may be difficult to believe that single-photon detectors exist in the absence of live proofs such as plants, animals, or people, in which a single photon evokes hundreds of transduction molecules in a millisecond. A single photon falling on the retina is detected by the human eye, which is a very sensitive detector. This photon is then absorbed by rhodopsin, a molecule. The energy in the ensuing nerve impulse is at least a million times greater than the energy in the original photon [6,40]. Signal amplification cascades of this magnitude can be found throughout the sensory system. Another example of signal detection sensitivity yet to be reached with human-made technology is the low hearing threshold in humans. Signals below thermal noise can be detected, and the noise even helps to hear these small signals instead of blurring them (stochastic resonance) [41].

Since Various MEMS/NEMS are designed to perform expected functions in the millisecond to picosecond range. The life expectancy of devices for high-speed contacts can vary from a few hundred thousand to many billions of cycles, e.g., over a hundred billion cycles for DMDs (digital micromirror device), putting stringent requirements on materials. Adhesion between a biological molecular layer and the substrate (referred to as bio adhesion) reduces friction and wear of biological layers (biocompatibility and biofouling). Most mechanical properties are known to be scale-dependent. Therefore, the properties of nanoscale structures need to be measured. There is a need to develop a fundamental understanding of adhesion, friction/stiction, wear, and the role of surface contamination and the environment. [42,43].

TRIBOLOGY IN BIOMEMS/NEMS

The field of nanotribology (atomic force microscopy-based techniques) has provided researchers with a viable approach to nanoscale challenges. Adhesion, friction, and wear studies of materials for bioMEMS/NEMS

require tribological investigations between natural atoms on silicon-based and polymer surfaces. There are several BioMEMS/NEMS applications and emerging nanotechnologies based on biological models [28,42,42].

Bushan and Pattojoshi [43] refer to biosensors as devices typically used to detect target biomolecules such as proteins, enzymes, nucleic acids, and chemical contaminants. Biosensors can be classified into two broad categories [42,43]:

- Microarray type, typically consisting of microfluidic and nanofluidic sensors usually involving the manipulation of small fluidic volumes (microliters to nanoliters), leading to optical methods for detection.
- Cantilever or field-effect devices with adsorption of target analysts to sensing elements as the primary transduction mechanism.

These sensors are either designed to detect a single biochemical or a class of (bio)chemicals Tribology, or to provide device-level analytical capabilities for a wide range of (bio)chemical organisms, referred to as a micro total analysis system (TAS). Optical methods are used in micro and nanofluidic biosensors, and mechanical or electrical methods are used in microarray-type biosensors [27].

Fluorescence, optical cavity resonator, and surface plasmon resonance are examples of optical methods. Fluid flow in micro and nanochannels is regulated in a variety of ways. Mechanical changes caused by the adsorption of target molecules or analysts to cantilevers or nanowires are among the mechanical techniques.

Changes to the intrinsic bimolecular charge in field-effect transistors or electrochemical changes are examples of electrical methods. Two methods are widely used to drive the fluid flow in micro and nanofluidic biosensors: pressure-driven and electric field-driven or electrokinetic [44]. In this sense, there are several devices that are required for a functional microfluidic device. These are:

Microvalves

Microvalves are found in most microfluidic components for biosensors. Microvalves can be either active microvalves (with an actuator) for flow regulation in microchannels or passive microvalves (integrated with micropumps). Active microvalves consist of a valve seat and a diaphragm actuated by an external actuator. Different actuators are based on piezoelectric, electrostatic, thermopneumatic, electromagnetic, bimetallic materials, shaped memory alloys, and solenoid plungers. An example of an electrostatic cantilever-type active microvalve is shown (Figure 1) [36].

Micropumps

The four main types of mechanical micropumps are diaphragm with mechanical check valves, electrostatic, valueless rectification pumps with or without diffuser/nozzle style valves, and rotary.

A micro diaphragm pump comprises two check valves and a reciprocating diaphragm operated by piezoelectricity (Figure 1B). While electrostatic micropumps have a diaphragm, they are driven by two electrodes (Figure 1F). A piezoelectrically operated diaphragm is often used in valueless micro pumps, but there are no passive mechanical valves. These pumps, on the other hand, use an elastic buffer or a variable gap system. Finally, a rotary micropump has a spinning rotor that essentially adds momentum to the fluid due to the blades' rapid movement (Figure 1A). An integrated electromagnetic motor or the presence of an external electric field may be used to drive rotary micropumps. Silicon or a polymer material can be used to make any of these micropumps. Contacts occur during the activity of the microvalves and micropumps mentioned above, and they are significant. Active mechanical microvalves have an externally actuated diaphragm that contacts a valve seat to limit fluid flow during the operation [27].

The adhesion of the diaphragm and valve seat can affect the operation of the microvalve. When a passive mechanical check valve's fluid flow is removed, the flap or membrane comes into contact with the valve seat, causing adhesion. During the use of valveless micropumps, adhesion occurs when the piezoelectrically driven diaphragm comes into contact with the rigid outlet [42]. Finally, during the rotary action, adhesion and friction can be observed. If the adhesion between the microchannel surface and the biofluid is solid, biomolecules can bind to the microchannel surface and restrict flow. As a result, microchannel surfaces with low bio adhesion are required. In polymer channels, fluid flow can cause triboelectric surface potential, possibly obstructing flow. Polymers generate surface potential, but the extent of this potential varies between polymers. Conductive surface layers may be deposited on the polymer channels to reduce triboelectric effects [45].

An example of a microarray-type biosensor, based on a field-effect transistor (FET), FETs are sensitive to the electrical field produced by the charge at the surface of the gate insulator. In this sensor, the gate metal electrode of a metal-oxide-semiconductor field-effect transistor (MOSFET) is removed and replaced with a protein (receptor layer) whose cognate is the analyte (e.g., virus or bacteria) that is meant to be sensed [26].

Various proteins may have 125 (positive or negative) charges per molecule. The binding of the receptor layer with the analyte produces a change in the effective charge, creating a change in the electrical field.

electrical field change may produce a measurable change in the current flow through the device. Adhesion between the protein layer and silica substrate affects the reliability of the biosensor [26]. In the case of implanted

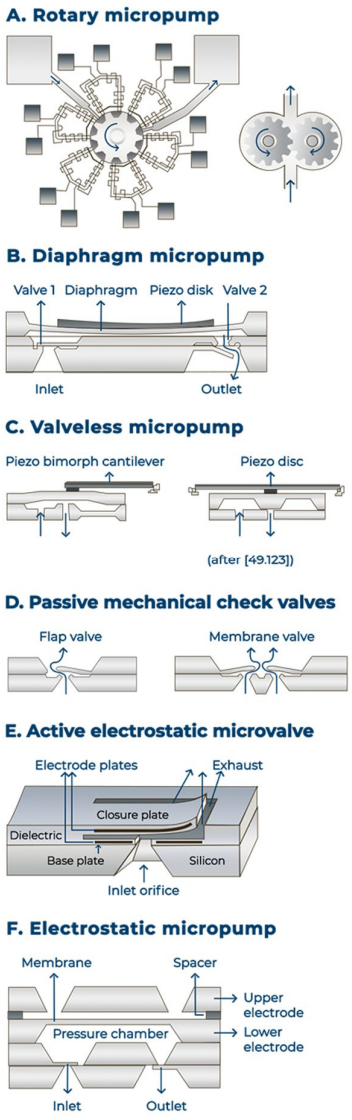

Figure 1: Passive microvalves used in micropumps include mechanical check valves and a diffuser/nozzle. Check valves consist of a flap or membrane capable of opening and closing with changes in pressure. A diffuser/nozzle uses an entirely different principle and only works with the presence of a reciprocating diaphragm [27].

biosensors, the biosensors contact the exterior environment, such as tissues and fluids. Any relative motion of the sensor surface with respect to that outer environment may result in surface damage. A schematic of the generation of friction and wear points is created when an implanted biosensor surface comes in contact with living tissue. The friction, wear, and adhesion of the biosensor surface may be critical in these applications [21,27,28,46,47].

Polymer bioMEMS have been designed to measure cellular surfaces. The device on the left has cantilevers anchored at the periphery of the circular structure, while the device on the right has cantilevers anchored at the two corners on the top and the bottom. The cell adheres to the center of the structure, and the contractile forces generated in the cell's cytoskeleton causes the cantilever to deflect. The deflection of the compliant polymer cantilevers is measured optically and related to the magnitude of the forces generated by the cell. Adhesion between cells and the polymer beam is desirable. To design the sensors, the micro and nanoscale mechanical properties of polymer structures are needed [13,35].

Drug Delivery Systems

Micro and nanofluidic devices provide a powerful platform for electrophoretic separations for various chemical and biochemical analyses. Electrophoresis is a versatile analytical method used to separate small ions, neutral molecules, and large biomolecules. [35]

There are interesting examples of MEMs and NEMs being employed as drug delivery systems:

Implantable, immunoisolation submicroscopic bio capsule: drug delivery treating significant medical conditions such as Type I diabetes. The purpose of the immunoisolation bio capsule is to create an implantable device capable of supporting foreign living cells that can be transplanted into humans. Biofouling can also result in the clogging of the nanochannels or nanopores, potentially rendering the device ineffective [13]. The adhesion of proteins and cells to an implanted device can also cause detrimental results such as inflammation and excessive fibrosis. Deposition of the self-assembled monolayers of selected organic molecules on the channel implants, making them hydrophobic, presents an innovative solution to combat the adverse effects of the biological fluids [24,35,43].

Targeted intravascular drug-delivery device: using nanoparticles to search and destroy disease (tumor) cells. Adhesion between nanoparticles and disease cells is required. Furthermore, the particles should travel close to the endothelium lining of vascular arteries to facilitate the interaction between the particles and diseased cells. Human capillaries can have radii as small as 45 nm.

The margination of a particle circulating in the bloodstream was also analyzed [48]. They calculated the speed and time for margination (drifting of particles towards the blood vessel walls) as a function of the density and diameter of a particle, based on various forces present between the circulating particle and the endothelium lining. They reported that the particles used for drug delivery should have a radius smaller than the critical value (in the range of 100 nm) [29,30]. Studies show that a lateral force on the particles assists them in faster margination towards the endothelium walls. Thus, no spherical particles are more desirable. In addition, reducing agglomeration and friction of nano-objects moving through a liquid and in contact with surfaces is essential for efficient transport to diseased sites. Because of their unique mechanical and electrical properties, single-walled and multiwall carbon nanotubes (SWNT and MWNT) are being used for thermal management of high-power devices, reinforced composites, and super-strong fiber and sheets, chemical and biological sensors,

electromechanical devices, field emission devices, molecular electronics, and computing [48].

A SWNT biosensor is a single-walled nanotube. The conductance of the CNT gadget changes when proteins adsorb on a superficial level. The adjustment of electrical opposition is a proportion of protein adsorption. For higher performance, the bond ought to be solid among adsorbents and SWNT. The conductance of carbon nanotube (CNT) devices changes when proteins adsorb on the surface. The change in electrical resistance is a measure of protein adsorption. For high performance, adhesion should be strong between the adsorbent and SWNT. In summary, adhesion, stiction/friction, and wear clearly limit the lifetimes and compromise the performance and reliability of MEMS/NEMS and bioMEMS/bioNEMS [35].

TRIBOLOGICAL INVESTIGATIONS OF NATURAL ATOMS ON SILICON-BASED AND POLYMER SURFACES

Proteins in tribology

Proteins on silicon-based surfaces play an essential role in various applications, including silicon micro-implants, biosensors, and therapeutics. Although silicon is a popular micro implant substrate, it can harm the human immune system. As a result, to replicate a biological surface, protein coatings are used as passivation layers on silicon-based surfaces, ensuring that these implants are compatible with the body and do not induce rejection. The nanoscale three-dimensional structural conformation of the protein determines the role of protein passivation [27].

Because of their function specificity, proteins are often used in bioMEMS. For biosensor applications, protein activities cover a broad range of operations that can be carried out at the nanoscale. Antibodies are proteins that have a strong affinity for particular protein antigens.

Antigens generated by pathogens (disease-causing agents such as viruses or bacteria) can be recognized by binding to a particular antibody on the biosensor. Proteins' basic binding action, used in laboratory assays, may be redesigned as sensing elements in bioMEMS *in vivo* [49].

Proteins with epitope-specific antigen-binding properties are useful in therapeutics. The reliability of an application is influenced by protein-substrate adhesion. The morphology of the substrate, for example, affects adhesion. Furthermore, when in direct contact with tissue and circulatory blood flow in in-vivo settings, the proteins on the biosensor surface should have high wear resistance.

Adhesion of A model of protein streptavidin (STA) on silicon-based surfaces

Bhushan et al. [42] investigated the morphological changes and adhesion of a model protein, streptavidin (STA), on silicon-based surfaces in a step-by-step manner. In addition to physical adsorption, they used nanopatterning and chemical linker methods to improve adhesion. A nanopatterned surface's limited edge surface area results in high surface energy and adhesion. Sulpho-NHS-biotin was used as a crosslinker in the chemical linker phase. The bonds between the STA and the biotin molecule are among the strongest noncovalent bonds identified [23,36].

3-aminopropyltriethoxysilane, a silane linker, was used to bind it to the silica surface (3-APTES). To form a bond between the silane linker and the silica surface, the silica surface was hydroxylated. Before STA, bovine serum albumin (BSA) was used to block non-specific binding sites of the STA protein with the silica surface. In this case, the adhesion values of biotin and STA is higher than other samples. On the edges of patterned silica, high adhesion values were also discovered. Both nanopatterned surfaces and chemical linkers improve STA adhesion [50].

Friction and wear of STA

Friction and wear of STA deposited using physical and chemical linker methods has been studied. The coefficient of friction between the Si3N4 tip and various samples. STA-coated silica samples have a lower coefficient of friction than uncoated silica samples. The STA coating forms a lubricant film. The coefficient of friction is proportional to the concentration of STA, and it decreases as the concentration rises [21].

Density and distribution of the biomolecules

The density and distribution of biomolecules differ with concentration, according to Bhushan et al. At higher concentrations of the solution, the coated layer is smoother, and the silica substrate surface is more heavily covered with biomolecules than at lower concentrations. The surface forms a continuous lubricant film at higher concentrations, meaning that the surface forms a continuous lubricant film. The coefficient of friction increases as the length of the biomolecular chain in samples prepared by the chemical linker process increases due to increased compliance [3,36].

The surface compresses when a normal load is applied, resulting in a greater contact area between the AFM tip and the biomolecules. Apart from that, STA is much bigger than APTES and biotin. The size difference results in a tightly packed surface with the biomolecules, which leads to a minimal lateral deflection of the linker in the case of STA-coated biotin, because of the high contact area and low lateral deflection, the friction force increases for the same applied normal load compared to a directly adsorbed surface. Biomolecule-coated surfaces are shown to reduce friction in these experiments; still, if the biomolecular coating is too thick or the surface has some cushioning effect, the coefficient of friction will increase, as seen in the chemical linker process [27].

TRIBOLOGICAL (BIO MEMS/NEMS) APPLICATIONS

Nanotechnologies

A variety of MEMS/NEMS and BioMEMS/NEMS are in use or being developed for commercial applications. Adhesion, friction, wear, and lubrication becomes essential in certain devices because they require relative motion. Surface interactions play a significant role in the friction and wear of lightly loaded micro and nanostructures (a few atomic layers). Molecularly thin films are used to coat these structures [51]. Scale affects a lot of mechanical properties. As a result, the properties of micro and nanoscale structures must be calculated at appropriate scales. Adhesion between biological molecular layers and the substrate and friction and wear of biological layers are essential in BioMEMS/NEMS [19, 24, 52].

Optical micrograph of a miniature motor

A further example is an optical micrograph of a micro-engine driven by an electrostatically activated comb drive connected to the output micro-gear by linkages. The micro-engine operates in the kHz frequency range and can be used as a general drive and power source to drive micromechanisms. Its parts are fabricated by surface micromachining from polysilicon film. A micro-gear unit is used to convert reciprocating motion from a linear actuator into circular motion. Another drive linkage oriented at 90 to the original linkage, driven by another linear actuator, allows maintenance of continuous motion. The linkages are connected to the output gear through pin joints that allow relative motion [53]. One inset shows a polysilicon, multiple micro-gear speed reduction unit and its components after laboratory wear tests conducted for 600,000 cycles at 1.8% relative humidity (RH). The wear of various parts can be clearly seen in the figure. Vapor deposited self-assembled monolayers of fluorinated (dimethylamino) silane have been used to minimize wear. The second inset shows a comb drive with a deformed frame, resulting in some teeth coming into contact. The contacting fingers can result in stiction [19].

Commercially available MEMS devices

Commercially available MEMS devices also exhibit tribological problems. A few devices with tribological issues are outlined below

- **An integrated capacitive type silicon accelerometer** fabricated used surface micromachining by analog devices, a couple of mm. in dimension. It is used to deploy airbags in automobiles and for various other devices in the consumer electronics market [54]. The central suspended beam mass (about 0.7 lg) is supported on the four corners by spring structures. The central beam has interdigitated cantilevered electrode fingers (about 125 lm long and 3 lm thick) on all four sides that alternate with those of the stationary electrode fingers, as shown, with about a 1.3 lm gap. The lateral motion of the central beam causes a change in the capacitance between these electrodes. This change is used to measure acceleration. Stiction between the adjacent electrodes and the stiction of the beam structure with the underlying substrate, under isolated conditions, is detrimental to the sensor's operation. Wear during unintended contacts of these polysilicon fingers is also a problem. A molecularly thick diphenyl siloxane lubricant film, resistant to high temperatures and oxidation, is applied by a vapor deposition process on the electrodes to reduce stiction and wear. For deposition, a small amount of liquid is dispensed into each package before it is sealed. As the package is heated in the furnace, the liquid evaporates and coats the sensor surface. As sensors are required to sense low g-force accelerations, they need to be more compliant, and stiction becomes a greater concern [54].
- **Two advanced miniature mirror gadgets (DMD)** Two digital micromirror device (DMD) pixels used in digital projection display (DLP) technology in computer projectors, HDTV sets, and movie projector. The entire array (chipset) consists of many oscillating aluminum alloy micromirrors as digital light switches. These are fabricated on top of a complementary metal-oxide-semiconductor (CMOS) static random-access memory integrated circuit. The surface micromachined array consists of half a million to more than two million independently controlled reflective micromirrors. Each micromirror is about 12 lm square with 13 lm pitch and flips backward and forward at a frequency on the order of 5 to 7 kHz due to electrostatic attraction between the micromirror structure and the underlying electrodes. For binary operation, the micromirror/yoke structure mounted on torsional hinges is oscillated ± 10 (respecting the plane on the chipset) and is limited by a mechanical stop. Contact between cantilevered spring tips at the end of the yoke (four on each yoke) with underlying stationary landing sites is required for true digital (binary) operation. Stiction and wear during contact between aluminum alloy spring tips and landing sites, hinge memory (metal creep at high operating temperatures), hinge fatigue, shock and vibration failure, sensitivity to particles in the chip package, and operating environment are some of the critical issues affecting the operation reliability of a micromirror device. A vapor phase deposited self-assembled monolayer of the fatty acid perfluorodecanoic acid (PFDA) on surfaces of tip and landing sites is used to reduce stiction and wear. However, these films are susceptible to moisture, and to keep moisture out and create a background pressure of PFDA, a hermetic chip package is used. The spring tip uses the stored spring energy to pop up the tip during pull-off. A lifetime estimate of over 100,000 operating hours with no degradation in image quality is typical. Each micromirror element at a mirror modulation frequency of 7 kHz needs to switch about 2.5 trillion cycles [7].
- **Carbon nanotubes (CNTs)** have extraordinary mechanical and electrical properties, making them

alluring for some applications. Endeavors have been made to create built-up composites, super-solid strands and sheets, nanotests, substance and natural sensors, nanoscale electromechanical gadgets, and atomic hardware.

- **Individual multiwall nanotubes (MWNTs)** are checking with electron magnifying instrument (SEM) is also a device that shows were MWNTs drawn from a thick shrubbery of nanotube timberland to make a long, level cluster. The subsequent strips were then layered on each other to make a super-strong sheet. The mechanical properties of nanotube strips, like flexible modulus and elasticity, depend on the bond and grating between MWNTs.

BIOTRIBOLOGICAL MODEL SYSTEMS FOR EMERGING TECHNOLOGIES

Exceptional designs for combining soft and hard materials have evolved in nature, with capabilities far exceeding current technologies. However, extracting design lessons from nature, particularly at the interface of physically, chemically, and electrically compatible soft (organic) and stiff materials, is a big issue. The cartilage that borders the bones in joints is known as articular cartilage (AC). AC is a material with a functional gradient (FGM). FGMs have position-dependent physical and mechanical properties that extend over microscopic or macroscopic distances due to a continuous spatial change in composition or microstructure [55,56].

In smoothly moving synovial joints, AC is the bearing surface with low friction and wear that allows smooth motion between adjacent bone segments. AC aids in the distribution of loads between opposing bones in a synovial joint due to its compliance. Synovial joints include the hip, knee, elbow, fingers, shoulder, and ankle. Synovial joints are sophisticated, complicated

structures that are yet poorly understood. The loads are unusually heavy, and the relative motion is intricate [2,15,47,53, 57].

Normal synovial joints operate with an amazingly low coefficient of friction. Some groups report friction coefficients as low as 0.001; generally, slightly higher values (between 0.002 to 0.006) appear in the literature. Values of up to 0.02 are reported for the friction coefficient in synovial joints. One reason for the considerable variation in the hip joint friction coefficient might be its distinct temperature dependence. Such low friction coefficients are still hard to reach with artificial systems. For comparison, Teflon sliding on Teflon (or Teflon sliding on steel) has a coefficient of friction of about 0.04; this is an order of magnitude higher than that for synovial joints [56].

Definitely, synovial joints are remarkable biotribosystems with unique properties, thanks to which a person is able to perform a huge range of motor actions with minimal energy losses due to friction. One of the factors contributing to this is that the basic elements of

synovial joints (articular surfaces, covered with articular cartilage; articular cavity; joint capsule; synovium; synovial fluid), are synergistically linked to each other and form an integral biomechanical system. At the same time, a permanent change in the properties of at least one of the listed elements leads to a change in the properties of others and synovial joints in general. It is in them that all the qualities that correspond to the so-called “smart friction units” are most clearly manifested but at the same time they are also most often susceptible to diseases and injuries that limit the physical activity of people and in many cases lead to disability [18], [56]. In biological systems especially, however, friction and wear are not simply related phenomena; low friction systems do not necessarily result in low levels of wear. Since worn material can be replaced (re-grown) by many biological systems, low friction is in many cases more preferable than low wear [56].

TRIBOLOGY IN GLASS ON THE MICROMETER SCALE- DIATOMS

Diatoms are single-celled organic entities that live either in the ocean or in freshwater. They can be appended to a base (benthic diatoms) or live openly gliding in the sea. Diatoms produce nanostructured silica. Many of the benthic diatoms produce adhesives. The silica production at ambient temperatures is interesting for materials scientists and structural biologists and is an active area of research [2]. The adhesive production of diatoms is, on the one hand, a tedious problem for marine devices (biofouling). Then again, these glues are intriguing for materials researchers and tribologists. Most artificial immersible glues are not reliable in seawater. Learning from diatoms that produce a solid, self-healing glue could lead to advancements in novel cement development. There are over 100 species diatoms worldwide. Some are planktonic structures and are free-floating as they cannot propel themselves against a current. Some have benthic structures, while others are appended to a base [58].

It has been shown that carrots and some diatom species produce substances that strongly inhibit ice recrystallization. These substances have not yet been identified, but experiments with purified solutions produced from samples collected in polar regions show that these substances bind to specific crystal orientations of the ice and are also incorporated into the ice lattice. Unlike fish antifreeze proteins, they do not significantly reduce the freezing point. These substances are very stable, even heating them to 100 degrees Celsius for five minutes does not affect their ability to inhibit recrystallization. The temperature stability of these substances might be important in technological applications, e.g., in coating windshields of airplanes with thin layers of such recrystallization inhibitors. The crystal orientation-specific etching of these substances

reminds of the proteins guiding and inhibiting snail shell growth via selectively promoting or preventing calcium carbonate growth in specific crystal orientations. Several diatom species have evolved elaborate linking structures [59]. Hinges and interlocking devices serve several functions: they keep the cells together (anti-dispersal strategy), they keep the cells apart so that enough light for photosynthesis can enter the cell. A diatom species named Corethron has evolved a click-stop mechanism for the silica spines that prevents them from moving too far back from their "required" position [21,60]. The entire construction is delightfully designed on a small scale and may give important blueprints for developing novel self-collected MEMS, such as the out-of-plane loop inductors [2].

DISCUSSION

One of the main challenges is to optimize the integration of biologists and engineers. Since nature offers unique solutions to several tribological problems, mimicking nature has become a centerpiece in this field. It is expected that the field will continue to grow and keep gardening interest in many more industrial applications. Energy optimization, an increased durability, higher efficiency in cycles, and better biomaterials are required to attain a sustainable future.

One of the most promising devices are proteins specially since they have proven capabilities to be employed as biosensors. As an example, antibodies are proteins that have a strong affinity for particular protein antigens. Antigens generated by pathogens (disease-causing agents such as viruses or bacteria) can be recognized by binding to a particular antibody on the biosensor. Proteins' basic binding action, used in laboratory assays, may be redesigned as sensing elements in bioMEMS *in vivo*.

Several MEMS/NEMS are employed to perform specific functions in the millisecond to picosecond range. Therefore the life cicle of such devices can vary from a few hundred thousand to many billions of cycles which demands materials with excellent mechanical properties. Indeed, most of the known mechanical properties are scale-dependent. Therefore, the properties of nanoscale structures need to be measured. There is a need to develop a fundamental understanding of adhesion, friction/stiction, wear, and the role of surface contamination and the environment.

For the past fifty years, various researchers have progressed our tribological information by building up strong hypothetical and viable theories, but the field requires more scientific output. This review acknowledges that the available information is still scarce and there are still areas such as clinical designing, which require more research to bolster the production of life saving technologies.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest. The sponsors had no role in the design of the study; in the collection, analysis or interpretation of data; in the writing of the manuscript or in the decision to publish the results.

REFERENCES

1. Patabadige DWE, Jia S, Sibbitts J, Sadeghi J, Sellens K, et al. (2016) Micro Total Analysis Systems: Fundamental Advances and Applications. Anal Chem 88: 320-338.
2. Gebeshuber C, Pauschitz A, Franek F (2006) Biotribological model systems for emerging nanometer scale technologies. NanoSingapore IEEE Conf Emerg Technol Nanoelectron Proc 396-400.
3. Nyberg E, Cervelló DLI, Minami I (2021) Tribology in space robotic actuators: Experimental method for evaluation and analysis of gearboxes. Aerospace 8: 3.
4. Hailing J (1991) Encyclopedia of tribology. 150: 1-2.
5. Bhushan B (2001) Modern Tribology Handbook. 1st Edtn CRC Press.
6. Nautiyal P, Alam F, Balani K, Agarwal A (2018) The Role of Nanomechanics in Healthcare. Adv Healthc Mater 7: 1-28.
7. Sinha SK, Satyanarayana N, Lim SC (2013) Nano-tribology and materials in MEMS. Nano-tribology Mater MEMS 1-275.
8. Scherge M, Gorb S (2013) Biological Micro- and Nanotribology. Springer 49: 306.
9. Gebeshuber C, Pauschitz A, Franek F (2006) Biotribological model systems for emerging nanometer scale technologies. NanoSingapore IEEE Conf Emerg Technol Nanoelectron Proc 396-400.
10. Auría-Soro C, Nesma T, Juanes-Velasco P, Landeira-Viñuela A, Fidalgo-Gomez H, et al. (2019) Interactions of nanoparticles and biosystems: Microenvironment of nanoparticles and biomolecules in nanomedicine. Nanomaterials 9: 10.
11. Laval JM, Mazeran PE, Thomas D (2000) Nanobiotechnology and its role in the development of new analytical devices. Analyst 125: 29-33.
12. Alberts BLJ, Johnson A (2002) Molecular Biology of the Cell. 4th edtn Garland Science 388.
13. Brodeur G, Ramakrishnan S, Hsu CS (2017) Tribology, mechanics , materials and devices. 1: 5.
14. Galambos P (2007) BioMEMS - key concepts , examples , future directions.
15. Ramsden JJ (2016) The nano/bio interface. Nanotechnology 61-90.

16. Subramani K, Mehta M (2018) Nanodiagnostics in microbiology and dentistry. Elsevier Inc.
17. Vincent JFV, Mann DL (2002) Systematic technology transfer from biology to engineering. Philos Trans R Soc A Math Phys Eng Sci 360: 159-173.
18. Yoda M, Bourgeois O, Kumar A, Ridge O, Deyhle H, et al. Encyclopedia of Nanotechnology. Encycl Nanotechnol.
19. Bhushan B (2020) Frontiers in nanotribology: Magnetic storage, bio/nanotechnology, cosmetics, and bioinspiration. J Colloid Interface Sci 577: 127-162.
20. Azizipour N, Avazpour R, Rosenzweig DH, Sawan M, Ajji A, et al. (2020) Evolution of biochip technology: A review from lab-on-a-chip to organ-on-a-chip. Micromachines 11: 1-15.
21. Bhushan B, Tokachichu DR, Keener MT, Lee SC (2006) Nanoscale adhesion, friction and wear studies of biomolecules on silicon based surfaces. Acta Biomater 2: 39-49.
22. Byrne B, Stack E, Gilmartin N, O'Kennedy R (2009) Antibody-based sensors: Principles, problems and potential for detection of pathogens and associated toxins. Sensors 9: 4407-4445.
23. Bhushan B, wang JKK, Gupta S, Lee SC (2009) Nanoscale adhesion, friction and wear studies of biomolecules on silane polymer-coated silica and alumina-based surfaces. J R Soc Interface 6: 719-733.
24. Bhushan B (2007) Nanotribology and nanomechanics of MEMS/NEMS and BioMEMS/BioNEMS materials and devices. Microelectron Eng 84: 387-412.
25. Prabhu R, Devaraju A (2020) Recent review of tribology, rheology of biodegradable and FDM compatible polymers. Mater Today Proc 39: 781-788.
26. Bhushan B (2008) Nanotribology and Nanomechanics.
27. Bhushan B (2008) Nanotribology and nanomechanics in nano/biotechnology. Philos Trans R Soc A Math Phys Eng Sci 366: 1499-1537.
28. Liu H, Bhushan B (2004) Investigation of nanotribological and nanomechanical properties of the digital micromirror device by atomic force microscopy. J Vac Sci Technol A Vacuum, Surfaces Film 22: 1388-1396.
29. Molino J (2019) Microcápsulas Vacías Empleadas en Aplicaciones de Ultrasonidos: Generalidades, Usos y Métodos de Fabricación. Eur Sci J ESJ 15: 394-424.
30. Daiguji H, Takada S, Molino J, Takemura F (2009) Fabrication of hollow poly(lactic acid) microcapsules from microbubble templates. J Phys Chem B 113: 15002-15009.
31. Lombardo D, Kiselev MA, Caccamo MT (2019) Smart Nanoparticles for Drug Delivery Application: Development of Versatile Nanocarrier Platforms in Biotechnology and Nanomedicine. J Nanomater .
32. Convery N, Gadegaard N (2019) 30 Years of Microfluidics. Micro Nano Eng 2: 76-91.
33. Bhushan B, Palacio M, Kinzig B (2008) AFM-based nanotribological and electrical characterization of ultrathin wear-resistant ionic liquid films. J Colloid Interface Sci 317: 275-287.
34. Jacofsky D, Jacofsky E , Jacofsky M (2020) Understanding Antibody Testing for COVID-19. J Arthroplast J.
35. Bhushan B (2004) Springer handbook of nanotechnology. Choice Rev 42: 42-0968-42-0968.
36. Bhushan B (2005) Nanotribology and nanomechanics. Wear 259: 1507-1531.
37. Soong R, Bachand G, Neves H, Olkhovets A, Craighead H, et al. (2000) Powering an inorganic nanodevice with a biomolecular motor. Science 290: 1555-1558.
38. Song J (2013) Why do proteins aggregate? 'Intrinsically insoluble proteins'? And 'dark mediators'? Revealed by studies on 'insoluble proteins'? Solubilized in pure water. F1000Research 2.
39. Díaz-Villanueva JF, Díaz-Molina R, García-González V (2015) Protein folding and mechanisms of proteostasis. Int J Mol Sci 16: 17193-17230.
40. Arshavsky VY, Burns MY (2014) Current understanding of signal amplification in phototransduction. Cell Logist 4: e29390.
41. Wellens T, Shatokhin V, Buchleitner A (2004) Stochastic resonance. Reports Prog Phys 67: 45-105.
42. Pattojoshi P, Roy GS, Editor A, Joseph S (1999) Handbook of Nanotechnology of Nanotechnology.
43. Bhushan B (1999) Handbook of Micro/ Nanotribology.
44. Prakash S, Pinti M, Bhushan B (2012) Review article: Theory, fabrication and applications of microfluidic and nanofluidic biosensors. Philos Trans R Soc A Math Phys Eng Sci 370: 2269-2303.
45. Kim MP, Um DS, Shin YE, Ko H (2021) High-Performance Triboelectric Devices via Dielectric Polarization: A Review. Nanoscale Res Lett 16.
46. Friedrich K (2018) Polymer composites for tribological applications. Adv Ind Eng Polym Res 1: 3-39.
47. Ateshian GA, Wang H, Lai WM (1998) The role of interstitial fluid pressurization and surface porosities on the boundary friction of articular cartilage. J Tribol 120: 241-248.

48. Decuzzi P, Lee S, Bhushan B, Ferrari M (2005) A theoretical model for the margination of particles within blood vessels. Ann Biomed Eng 33:179-190.
49. Seker E, Sung JH, Shuler ML, Yarmush ML (2011) Solving medical problems with BioMEMS. IEEE Pulse 2: 51-59.
50. Bhushan B, Tokachichu DR, Keener MT, Lee SC (2005) Morphology and adhesion of biomolecules on silicon based surfaces. Acta Biomater 1: 327-341.
51. Wang X, Xu P, Han R, Ren J, Li L, et al. (2019) A review on the mechanical properties for thin film and block structure characterised by using nanoscratch test. Nanotechnol Rev 8: 628-644.
52. Bhushan B, Israelachvili JN, Landman U (1995) Nanotribology: Friction, wear and lubrication at the atomic scale. Nature 374: 607-616.
53. Linn FC (1968) Lubrication of animal joints. The mechanism J Biomech 1: 193-205.
54. Finkbeiner S (2013) MEMS for automotive and consumer electronics. Eur Solid-State Circuits Conf.
55. Parihar RS, Setti SG, Sahu RK (2018) Recent advances in the manufacturing processes of functionally graded materials: A review. IEEE J Sel Top Quantum Electron 25: 309-336.
56. Lin W, Klein J (2021) Recent Progress in Cartilage Lubrication. Adv Mater 33: 2005513.
57. Shi L, Guo ZG, Liu WM (2015) The recent progress of tribological biomaterials. Biosurface and Biotribology 1: 81-97.
58. Claverie M, McReynolds C, Petitpas A, Thomas M, Fernandes SCM (2020) Marine-derived polymeric materials and biomimetics: An overview. Polymers (Basel) 12: 5.
59. Benoiston S, Ibarbalz F, Bittner L, Guidi L, Jahn O, et al. (2017) The evolution of diatoms and their biogeochemical functions. Philos Trans R Soc B Biol Sci 372: 1728.
60. Raymond JA, Fritsen CH (2001) Semipurification and ice recrystallization inhibition activity of ice-active substances associated with antarctic photosynthetic organisms. Cryobiology 43: 63-70.