Triggered, Nanostructured Biodegradables (TNBs) for Surgical Implants

Richard Gordon*,[1], Stephen M. Levin[2] and Ille C. Gebeshuber[3]

[1]*Department of Radiology, University of Manitoba GA216, HSC, 820 Sherbrook Street, Winnipeg R3A 1R9 Canada; Gulf Specimen Marine Laboratory, Panacea, FL 32346 USA;* [2]*Ezekiel Biomechanics Group, 8608 Dixie Place, Mclean VA 22102 USA;* [3]*Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia & Institute of Applied Physics, Vienna University of Technology*

Abstract: In medicine, objects that need to be removed later - such as stents - are commonly placed in patients, with the time of removal dependent on progress of the patient. In these cases biodegradable materials that last for a specific time may not be suitable. We propose a new class of nanostructured materials that can hold their form as long as wanted, Triggered, Nanostructured Biodegradables (TNBs), that can be disintegrated to micro- or nanoscaled components when externally triggered on command to do so. DNA nanotensegrity microstructures, metastable foams, nanobots and other bioinspired disintegratable scaffold structures are given as potential examples.

Keywords: Triggered nanostructured biodegradables, surgical implants, stents, tensegrity, nanobots, modular nanobot dental braces, tektites, Prince Rupert's drops.

INTRODUCTION

Surgeons frequently implant materials in the body that need to come out at a later date. If the material is not biodegradable, then in present practice this requires an additional surgical procedure to remove it, with attendant risks. An example where one would not want an ordinarily biodegradable material is the stent:

1 The time it is to be left in place may not be determinable in advance.

2 Gradual biodegradation could lead to counterproductive transient blockage.

For example, an increase in bilirubin after placement of a stent in the common bile duct would suggest that the stent itself has become occluded [1], perhaps due to bile glycoprotein mucin [2]. Weaning from shunts [3] also suggests their removal after an unpredictable time. It would therefore be an advance to have a material whose degradation were instantaneous, complete, and triggered on command. We call such a material a Triggered, Nanostructured Biodegradable (TNB).

If a stent has done its job, ordinary biodegradability might lead to transient pieces that would block the duct, a counterproductive outcome, and even if not, the time course of biodegradation may not match the patient's needs. Complications of stents sometimes requiring their premature removal include infection [4], thrombosis [5], perforation [6] stent migration [7] and unplanned stent supercoiling [8]. "Potential complications with removal include tracheal disruption, retained stent pieces, mucosal tears, re-obstruction requiring new stent placement, the need for postoperative ventilation, pneumothorax, damage to the pulmonary artery, and death" [9]. Nonmechanical risks of ordinary biodegradable stents [10] include restenosis [11] and thrombosis [12].

Tektites are natural glass objects that form on meteorite impact [13]. Rock is melted into splashed molten drops because of the huge impact energy. These cool rapidly, a process called quenching. Their natural shapes include "spheres, oblate ellipsoids, dumbbells, teardrops, and tori" [14]. Some of them are unstable: the slightest scratch will cause them to explode to dust (Edward Anders, personal communication, 1962; cf. [15]). This phenomenon, called Prince Rupert's drops, has been known for 350 years [16] and has been extensively investigated using rapidly cooled glass drops [17]. Tektites then show that at least one real material exists whose degradation is instantaneous, complete, and triggered on command.

We could broaden the concept to consider materials that have two states, with a transition between them that can be triggered on command. For example, materials with "memory" of a previous state can be triggered to return to that state. Such materials are being used in surgery and prosthesis, but, of course, only change shape rather than disappear [18].

It may be possible to build TNBs as tensegrity structures, These were originally designed with their stability properties in mind:

> "The word 'tensegrity' is an invention: a contraction of 'tensional integrity.' Tensegrity describes a structural-relationship principle in which structural shape is guaranteed by the finitely closed, comprehensively continuous, tensional behaviors of the system and not by the discontinuous and exclusively local compressional member behaviors. Tensegrity provides the ability to yield increasingly without ultimately breaking or coming asunder" [19].

However, tensegrity structures are only stable for certain ranges of their parameters. A change in one of these parameters could lead to collapse of the whole structure [20] (Fig. **1**). There are models for collapsable tensegrity scaffoldings [21], tensegrity extendable bridges [22], and the Hoberman

*Address correspondence to this author at the Department of Radiology, University of Manitoba GA216, HSC, 820 Sherbrook Street, Winnipeg R3A 1R9 Canada; Gulf Specimen Marine Laboratory, Panacea, FL 32346 USA; Tel: 1-(850) 984-5297; Fax: 1-(850) 984-5233;
E-mail: gordonr@cc.umanitoba.ca

1876-4029/11 $58.00+.00

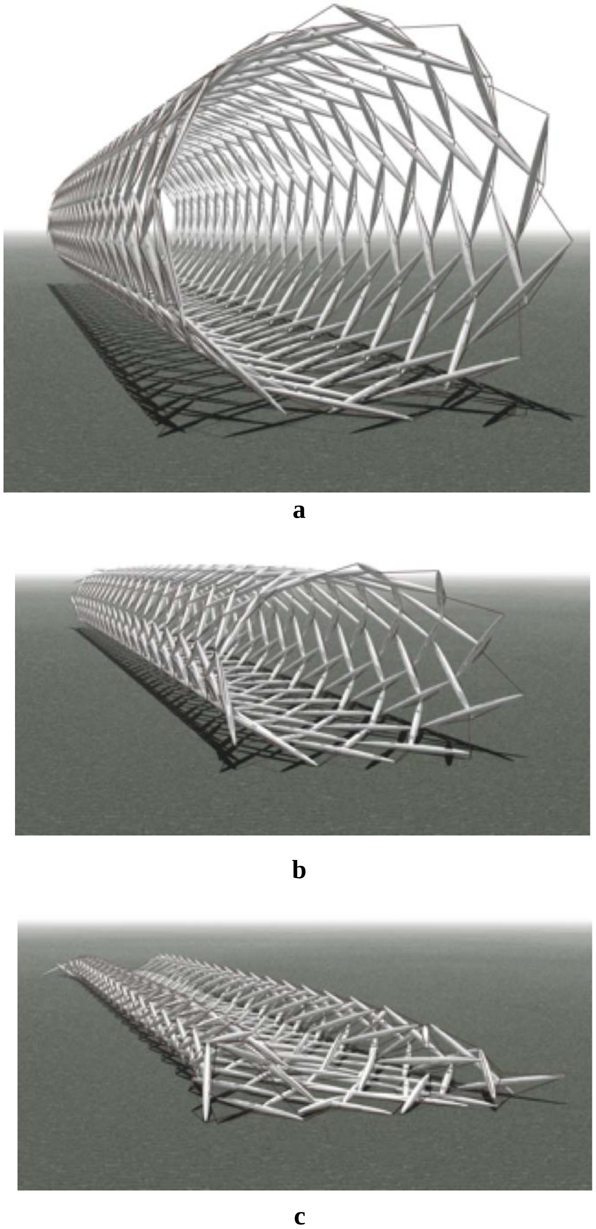

Fig. (1). Example for (**a**) a tensegrity, (**b**) a partially collapsed version of same, (**c**) a fully collapsed version. Images reproduced with kind permission of Gerald de Jong [62].

sphere [23]. Higher energy metastable tensegrity structures have been demonstrated [24], and such tensegrity metastability was hypothesized for the cell state splitter that may trigger cell differentiation in embryos [25]. Manufacturing collapsable tensegrity structures with microscale components would give them practical application. While tensegrity structures may not be stiff enough for most engineering constructs, they might be perfect for biological applications: artificial limbs and bracing at one scale, stents and the like at another.

It is actually rather difficult to design a tensegrity structure that retains a three dimensional shape [26]. Thus alteration of a tensegrity structure to make it collapse may be quite feasible.

Scaffolds could be built from micro- and nano-Origami structures, such as the DNA box with DNA triggered lid [27] or the DNA tetrahedron container [28], or nano-Origami structures made from stressed material, that, when the signal comes, collapses (actuates) [29]. Progress has been made towards large structures based on the "DNA tensegrity triangle" [30]. DNA nanomachines [31] present an opportunity to build larger structures that could disintegrate "on command". For example, the DNA could be chosen to contain the sequences broken by specific endonucleases. The flooding of the stent with an endonuclease solution could be the trigger for disintegration. Now that we can make artificial restriction enzymes [32], it may be possible to guarantee nontoxicity with the right stent DNA material/endonuclease combination.

Click-stop mechanisms, where the structure that ensures the "stop" disintegrates with the trigger, would be feasable. A click-stop mechanism has been found in the diatom *Corethron pennatum* [33].

We can also think about structures that are inert and would leave the body and where only the connections are made from the "triggered material" – this would give us a smart nano/microcomposite. A hierarchical material could be envisaged where the highest level of hierarchy is ensured by the triggerable material, and when the trigger comes, the whole collapses to smaller structures that can easily leave the body.

Modular robots [34] are presently macroscopic devices, whose unit robots combine or work together in many configurations (Fig. **2**). One of those configurations, generally not considered, would be for all robots to disconnect. Modular nanobots [35] could thus become a basis for structures that not only disintegrate on command, but perhaps also change configuration on demand while they are still needed. For example, braces for teeth require frequent manual adjustment, which could be done instead, perhaps automatically, by modular nanobot braces.

The oscillations in tensegrity icosahedrons [36] switch them from left handed to right handed spirals. Perhaps we could make a material that is not attacked by the immune system or enzymatically digested when it has one chirality, and that is attacked or digested when it has the other chirality. The transition between these two states would have to be triggered.

For stents outside the circulatory system, such as bile ducts, ureters, etc., changing the stent from a stiff, inert structure to a collapsed and readily passed material might be as simple as changing the phase of some of its components. Many tissues in the body, for example, muscles, undergo phase transitions, much like water into ice [37]. Usually this is related to calcium ion shifts or shifting chirality. If constructed from carbon nanotubes and collagen in some form that could undergo a phase transition, for instance, the stent could disintegrate into inert components. Intravascular stents are more of a challenge. They must be relatively inert, and readily phagocytized or removed from the circulatory system upon collapse without disrupting the system, causing clots or tissue damage. If the tensegrity stent is constructed from nanotubes, they are needle-like and could pass through the

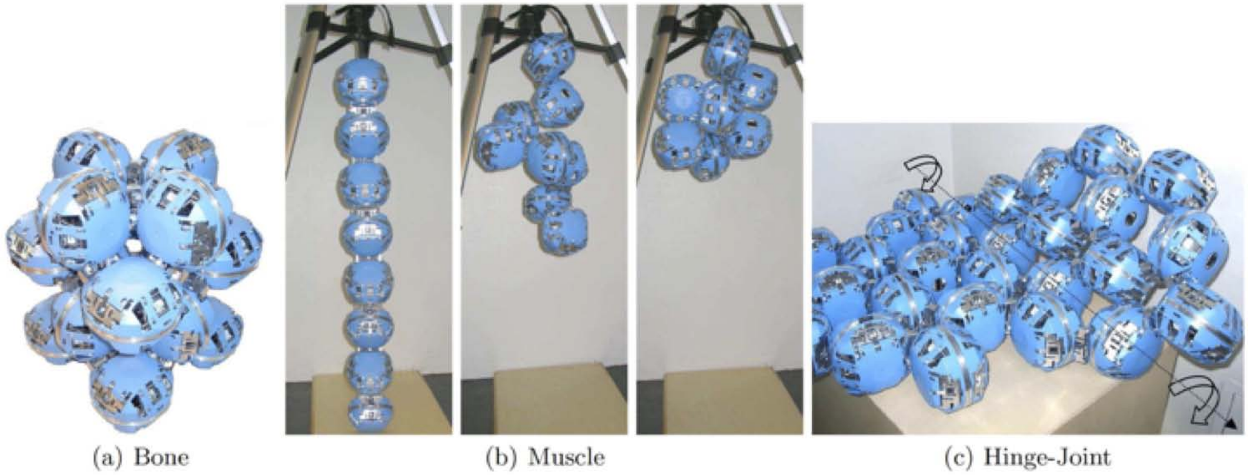

Fig. (2). Three structural modifications of the modular ATRON robot. (**a**) The bone configuration with high structural strength, (**b**) the muscle configuration made from 8 ATRON modules that contracts by forming a compact helix shape and (**c**) the hinge-joint with one degree of freedom. From [34d] with permission. On command, all robots could disengage from one another simulating a logical TNB.

walls of blood vessels without harm. Magnetic nanotubes [38] could reside in the soft tissues and be pulled out of harms way. An alternative is that the stent components could be directed to an arteriole that could be safely blocked.

Gels made of networks of polymers, such as hyaluronan [39], could be triggered [40] to undergo a sol/gel transition by either altering the lengths of the polymers, which could suddenly change their connection properties below the critical percolation bond probability [41], or by altering the ionic conditions so that the ratio of hydrophobic/hydrophilic contacts between polymers changes. A further possible material would be polysaccharides such as cellulose.

Another approach is to make implants out of a rigid foam that can be liquefied on command. For example, the foam might be a stabilized emulsion that breaks when a particular (biocompatible) reagent is introduced. A stiff emulsion of two encapsulated chemicals that on reaction dissolve their matrix is also conceivable, where a specific molecule, perhaps a tailored transmembrane protein, is used to suddenly lower the energy barrier keeping the compartments separate.

If nanomagnets could be configured that explode apart upon change of their configuration [42], this would allow another approach to TNB. The trigger could be a strong, short duration magnetic field. Biocompatible nanomagnets are available [43].

Other triggering mechanisms that could be considered include protective layer materials, passivation layer materials, and photoactivation.

In the spirit of bioinspiration [44], we find some more hints of how TNBs might be designed. For example, if a stiff tissue, say for a stent, were constructed of cells that could be triggered to undergo apoptosis [45] without affecting the rest of the body, then the disintegrating cells would be transported away by phagocytosis. Transient stiff embryonic tissues such as notochord [46] may provide a model. Differentiation waves through genetically modified tissues might cause those tissues to disintegrate to separate cells, such as may occur in embryogenesis during neural crest formation [25b].

We will next review biological apparati that are triggered rapidly, sometimes explosively. We could envision nanosprings and nanoactuators inspired by the molecular spring (spasmoneme) in *Vorticella convallaria*:

> "Molecular springs have recently emerged as the basis for the fastest and most powerful movements at the cellular level in biology. The spasmoneme of the protozoan, *Vorticella convallaria,* is a model molecular spring, relying on energy stored in protein interactions to power contraction over a few hundred micrometers in a few milliseconds. While basic characteristics of *Vorticella contraction* are known, the underlying biochemical mechanism is unclear" [47].

The speed of the spasmoneme is of the order of 0.1 m/s. Pollen also disperses explosively [48] at 3 m/s, and the jumping of some insects uses a trigger mechanism [49] to achieve 5 m/s. Spray from bombardier beetles [50] exits at up to 20 m/s. Exploding seeds of *Hura crepitans* [51] have initial velocities up to 70 m/s. Discobolocysts in the green alga *Ochromonas* [52] discharge at an estimated 300 m/s. Exploding ants [53] suggest the possibility of stents under pressure that disintegrate like burst balloons.We could use such fast actuators [54] to activate the destruction of stent material. The signal could be electrical and could be fed into the person *via* coils (as in cochlea implants [55]).

Resilin, the most stretchable natural rubber, can stretch twice its original length without breaking [56]. Chromolinkers, the material connecting chromosomes [57], can reportedly stretch 30x their relaxed length and return to their original length (Andrew J. Maniotis, personal communication). Cell colonies of the diatom *Ellerbeckia arenaria* grow many millimeters long and can be mechanically elongated three times their original length. When released, they snap back like a spring by an unknown mechanism [58], perhaps related to the elastic material between cells in another colonial diatom, *Bacillaria paxillifer*, previously known as *B. paradoxa* [59].

Some organisms have motor proteins that exhibit signal-dependent length changes. Prestin, for example, is the motor protein in outer hair cells of the inner ear, the cochlea. Voltage applied to the prestin molecules results in length change. In the inner ear, this voltage comes from electrical signals *via* the auditory nerve from the brain. Voltage-induced shape changes can be elicited in cultured human kidney cells when prestin is expressed in them [60]. A material with prestin expressed in it might be of interest for use as stent material.

In general, we may classify TNBs as:

1 *metastable* in the implanted environment, so that the function of the trigger is to start the collapse to a stable, disintegrated state that propagates throughout the structure;

2 *stable* in the implanted environment, with the function of the trigger mechanism being to alter the components by changing them so the structure falls apart;

3 *logical*, i.e., separation on computer command of constituent nanobots.

Metastable structures are perhaps less desirable, because they can fall apart at an arbitrary time [61] , before we get to trigger them deliberately.

In summary, there are many plausible materials for constructing Triggered, Nanostructured Biodegradables (TNBs).

ACKNOWLEDGEMENT

We would like to thank David N. Schwartz for making this paper possible.

REFERENCES

[1] Tapping, C. R.; Byass, O. R.; Cast, J. E., Percutaneous transhepatic biliary drainage (PTBD) with or without stenting-complications, re-stent rate and a new risk stratification score. *Eur. Radiol.*, **2011**, *21*(9), 1948-55.

[2] Zhang, H.; Tsang, T. K.; Jack, C. A., Bile glycoprotein mucin in sludge occluding biliary stent. *J. Lab. Clin. Med.*, **2003**, *142* (1), 58-65.

[3] Al-Zubi, N.; Al-Kharabsheh, A.; Momani, L.; Al-Nuaimy, W., Intelligent shunt agent for gradual shunt removal. *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, **2010**, *2010*, 430-3.

[4] Gardner, G. P.; Morris, M. E.; Makamson, B.; Faizer, R. M. Infection of an aortic stent graft with suprarenal fixation. *Ann. Vasc. Surg.*, **2010**, *24* (3), 418 e1-6.

[5] Barash, P.; Akhtar, S. Coronary stents: factors contributing to perioperative major adverse cardiovascular events. *Br. J. Anaesth,* **2010**, *105 (Suppl 1)*, i3-15.

[6] D'Ambrogio, A.; Dorta, G.; Givel, J. C., [Colorectal stent: therapeutic alternative for acute obstruction?]. *Rev. Med. Suisse.*, **2005**, *1* (24), 1605-1607.

[7] (a) Pillai, J. B.; Smith, J.; Hasan, A.; Spencer, D., Review of pediatric airway malacia and its management, with emphasis on stenting. *Eur. J. Cardiothorac. Surg.*, **2005**, *27*(1), 35-44; (b) Diller, R.; Senninger, N.; Kautz, G.; Tubergen, D., Stent migration necessitating surgical intervention. *Surg. Endosc.*, **2003**, *17* (11), 1803-1807.

[8] Berg, J. C., Bird nest deformity of a self-expanding esophageal stent and a technique of removal. *Gastrointest. Endosc.*, **1999**, *50* (1), 108-10.

[9] Doyle, D. J.; Abdelmalak, B.; Machuzak, M.; Gildea, T. R., Anesthesia and airway management for removing pulmonary self-expanding metallic stents. *J. Clin. Anesth.*, **2009**, *21* (7), 529-532.

[10] Hermawan, H.; Dube, D.; Mantovani, D., Developments in metallic biodegradable stents. *Acta Biomater.*, **2010**, *6* (5), 1693-1697.

[11] Rogacka, R.; Chieffo, A.; Latib, A.; Colombo, A., Bioabsorbable and biocompatible stents. Is a new revolution coming? *Minerva Cardioangiol.*, **2008**, *56* (5), 483-491.

[12] (a) Wykrzykowska, J. J.; Onuma, Y.; Serruys, P. W., Advances in stent drug delivery: the future is in bioabsorbable stents. *Expert Opin. Drug Deliv.*, **2009**, *6* (2), 113-126; (b) Nakazawa, G.; Finn, A. V.; Kolodgie, F. D.; Virmani, R., A review of current devices and a look at new technology: drug-eluting stents. *Expert Rev. Med. Devices*, **2009**, *6* (1), 33-42.

[13] Anders, E., The record in the meteorites-II On the presence of aluminium-26 in meteorites and tektites. *Geochim. Cosmochim. Acta*, **1960**, *19* (1), 53-62.

[14] Elkins-Tanton, L. T.; Aussillous, P.; Bico, J.; Quéré, D.; Bush, J. W. M., A laboratory model of splash-form tektites. *Meteoritics & Planetary Science*, **2003**, *38* (9), 1331-1340.

[15] Hammond, C. R., Meteors and meteorites. Contributions of The Meteoritical Society: The chemical composition and some physical characteristics of tektites. *Popular Astronomy*, **1950**, *58*, 345-349.

[16] Chandrasekar, S.; Chaudhri, M. M., The explosive disintegration of Prince Rupert drops. *Philos. Mag. B-Phys. Condens. Matter Stat. Mech. Electron. Opt. Magn. Prop.*, **1994**, *70* (6), 1195-1218.

[17] (a) Chaudhri, M. M., The role of residual stress in a Prince Rupert's drop of soda-lime glass undergoing a self-sustained and stable destruction/fracture wave. *Phys. Status Solidi A-Appl. Mat.*, **2009**, *206* (7), 1410-1413; (b) Chaudhri, M. M., Explosive disintegration of thermally toughened soda-lime glass and Prince Rupert's drops. *Phys. Chem. Glasses-Eur. J. Glass Sci. Technol., Part B*, **2006**, *47* (2), 136-141.

[18] (a) Mueller, B.; Deyhle, H.; Mushkolaj, S.; Wieland, M., The challenges in artificial muscle research to treat incontinence. *Swiss Medical Weekly*, **2009**, *139* (41-42), ISSN 1424-7860(print)|1424-3997(electronic); (b) Tarnita, D.; Tarnita, D. N.; Bizdoaca, N.; Mindrila, I.; Vasilescu, M., Properties and medical applications of shape memory alloys. *Romanian Journal of Morphology and Embryology*, **2009**, *50* (1), 15-21; (c) Li, Q. A.; Zeng, Y. J.; Tang, X. Y., The applications and research progresses of nickel-titanium shape memory alloy in reconstructive surgery. *Australas. Phys. Eng. Sci. Med.*, **2010**, *33* (2), 129-136; (d) Auricchio, F.; Conti, M.; Morganti, S.; Reali, A., Shape memory alloy: from constitutive modeling to finite element analysis of stent deployment. *CMES-Comp. Model. Eng. Sci.*, **2010**, *57* (3), 225-244; (e) Wen, C. E.; Xiong, J. Y.; Li, Y. C.; Hodgson, P. D., Porous shape memory alloy scaffolds for biomedical applications: a review. *Physica Scripta*, **2010**, *T139*; (f) Wang, Y.; Zheng, G.; Zhang, X.; Zhang, Y.; Xiao, S.; Wang, Z., Comparative analysis between shape memory alloy-based correction and traditional correction technique in pedicle screws constructs for treating severe scoliosis. *Eur. Spine J.*, **2010**, *19* (3), 394-399.

[19] Buckminster Fuller, R.; Loeb, A. L.; Applewhite, E. J., *Synergetics: Explorations in the Geometry of Thinking*. Macmillan Publishing Co.: London, 1982.

[20] Guest, S. D., The stiffness of tensegrity structures. *IMA J. Appl. Math.*, **2011**, *76* (1), 57-66.

[21] Teho, I. Tensegrity Deployable Device [Movie]. http://www.youtube.com/watch?v=7R-EJAyC-V8&feature=related.

[22] (a) Zhou, Y.; Xie, Y. M.; Huang, X., Two general methods for creating tensegrity structures of towers, arches, bridges and stadium roofs. In *Innovations in Structural Engineering and Construction: Proceedings of the 4th International Structural and Construction Engineering Conference (ISEC-4), Melbourne, Australia, 26-28 September 2007*, Xie, Y. M.; Patnaikuni, I., Eds. Taylor and Francis: London, 2008; pp 87-92; (b) Heartney, E.; Snelson, K., *Kenneth Snelson: Forces Made Visible*. Hard Press Editions: **2009**.

[23] Hoberman Associates, Expanding Geodesic Dome [Movie[**2008**.

[24] Xu, X. A.; Luo, Y. Z., Multistable tensegrity structures. *Journal of Structural Engineering-ASCE*, **2011**, *137* (1), 117-123.

[25] (a) Gordon, R.; Brodland, G. W., The cytoskeletal mechanics of brain morphogenesis. Cell state splitters cause primary neural induction. *Cell Biophys.*, **1987**, *11*, 177-238; (b) Gordon, R., *The Hierarchical Genome and Differentiation Waves: Novel Unification of Development, Genetics and Evolution*. World Scientific & Imperial College Press: Singapore & London, **1999**; (c) Gordon, N. K.; Gordon, R., *Embryogenesis Explained [in*

preparation]. World Scientific Publishing Company: Singapore, **2012**.

[26] (a) Li, Y.; Feng, X. Q.; Cao, Y. P.; Gao, H. J., A Monte Carlo form-finding method for large scale regular and irregular tensegrity structures. *International Journal of Solids and Structures,* **2010**, *47* (14-15), 1888-1898; (b) Rieffel, J.; Valero-Cuevas, F.; Lipson, H., Automated discovery and optimization of large irregular tensegrity structures. *Computers & Structures,* **2009**, *87* (5-6), 368-379; (c) Tran, H. C.; Lee, J., Initial self-stress design of tensegrity grid structures. *Computers & Structures,* **2010**, *88* (9-10), 558-566; (d) Tran, H. C.; Lee, J., Advanced form-finding of tensegrity structures. *Computers & Structures,* **2010**, *88* (3-4), 237-246; (e) Xu, X.; Luo, Y. Z., Form-finding of nonregular tensegrities using a genetic algorithm. *Mechanics Research Communications,* **2010**, *37* (1), 85-91.

[27] Andersen, E. S.; Dong, M.; Nielsen, M. M.; Jahn, K.; Subramani, R.; Mamdouh, W.; Golas, M. M.; Sander, B.; Stark, H.; Oliveira, C. L. P.; Pedersen, J. S.; Birkedal, V.; Besenbacher, F.; Gothelf, K. V.; Kjems, J., Self-assembly of a nanoscale DNA box with a controllable lid. *Nature,* **2009**, *459* (7243), 73-77.

[28] Ke, Y. G.; Sharma, J.; Liu, M. H.; Jahn, K.; Liu, Y.; Yan, H., Scaffolded DNA Origami of a DNA Tetrahedron Molecular Container. *Nano Letters,* **2009**, *9* (6), 2445-2447.

[29] Stellman, P.; Arora, W.; Takahashi, S.; Demaine, E. D.; Barbastathis, G., Kinematics and dynamics of nanostructured Origami™. In *Proceedings of IMECE 2005, 2005 ASME International Mechanical Engineering Congress and Exposition, November 5-11, 2005, Orlando, Florida USA,* **2005**; pp 541-548.

[30] Zheng, J. P.; Birktoft, J. J.; Chen, Y.; Wang, T.; Sha, R. J.; Constantinou, P. E.; Ginell, S. L.; Mao, C. D.; Seeman, N. C., From molecular to macroscopic *via* the rational design of a self-assembled 3D DNA crystal. *Nature,* **2009**, *461* (7260), 74-77.

[31] (a) Seeman, N. C., Structural DNA nanotechnology: an overview. *Methods Mol. Biol.,* **2005**, *303*, 143-66; (b) Modi, S.; Swetha, M. G.; Goswami, D.; Gupta, G. D.; Mayor, S.; Krishnan, Y., A DNA nanomachine that maps spatial and temporal pH changes inside living cells. *Nature Nanotechnology,* **2009**, *4* (5), 325-330; (c) Chakraborty, B.; Sha, R.; Seeman, N. C., A DNA-based nanomechanical device with three robust states. *PNAS,* **2008**, (May 12), doi:10.1073/pnas.0707681105.

[32] (a) Chan, S. H.; Stoddard, B. L.; Xu, S. Y., Natural and engineered nicking endonucleases--from cleavage mechanism to engineering of strand-specificity. *Nucleic Acids Res.,* **2011**, *39* (1), 1-18; (b) Katada, H.; Komiyama, M., Artificial restriction DNA cutters as new tools for gene manipulation. *Chem. Bio. Chem.,* **2009**, *10* (8), 1279-88.

[33] (a) Gebeshuber, I. C.; Crawford, R. M., Micromechanics in biogenic hydrated silica: hinges and interlocking devices in diatoms. *Proceedings of the Institution of Mechanical Engineers Part J-Journal of Engineering Tribology,* **2006**, *220* (J8), 787-796; (b) Gordon, R.; Witkowski, A.; Gebeshuber, I. C.; Allen, C. S., The diatoms of Antarctica and their potential roles in nanotechnology. In *Antarctica: Time of Change*, Masó, M., Ed. Editions ACTAR: Barcelona, **2010**; pp 84-95.

[34] (a) Karbasi, H.; Huissoon, J. P.; Khajepour, A., Blend of independent joint control and variable structure systems for uni-drive modular robots. *Robotica,* **2010**, *28*, 149-159; (b) Lal, S. P.; Yamada, K.; Endo, S., *Evolving motion control for a modular robot*. Springer-Verlag London Ltd: Godalming, 2008; p 245-258; (c) Yim, M.; Zhang, Y.; Duff, D., Modular robots. *IEEE Spectr.,* **2002**, *39* (2), 30-34; (d) Christensen, D. J.; Campbell, J.; Stoy, K., Anatomy-based organization of morphology and control in self-reconfigurable modular robots. *Neural Comput. Applic.,* **2010**, *19* (6), 787-805; (e) Yu, C. H.; Haller, K.; Ingber, D.; Nagpal, R., Morpho: a self-deformable modular robot inspired by cellular structure. In *2008 IEEE/RSJ International Conference on Robots and Intelligent Systems, Vols 1-3, Conference Proceedings*, Chatila, R.; Kelly, A.; Merlet, J. P., Eds. IEEE: Los Alamitos, California, 2008; pp 3571-3578.

[35] Gordon, R., Mechanics in embryogenesis and embryonics: prime mover or epiphenomenon? *Int. J. Dev. Biol.,* **2006**, *50* (2/3), 245-253.

[36] Levin, S. M., The icosahedron as the three-dimensional finite element in biomechanical support. In *Proceedings of the Society of General Systems Research Symposium on Mental Images, Values and Reality, 1986 May 26-30*, Dillon, J. R., Ed. U of P. Society of General Systems Research: Philadelphia, **1986**; pp G14-26.

[37] Pollack, G. H., *Cells, Gels and the Engines of Life: A New, Unifying Approach to Cell Function*. Ebner & Sons Publishers: Seattle, 2001.

[38] Shan, Y.; Chen, K. Z.; Yu, X. G.; Gao, L. A., Preparation and characterization of biocompatible magnetic carbon nanotubes. *Applied Surface Science,* **2010**, *257* (2), 362-366.

[39] Scott, J. E.; Cummings, C.; Brass, A.; Chen, Y., Secondary and tertiary structures of hyaluronan in aqueous solution, investigated by rotary shadowing-electron microscopy and computer simulation. Hyaluronan is a very efficient network-forming polymer. *Biochem. J.,* **1991**, *274* (Pt 3), 699-705.

[40] Yui, N.; Mrsny, R. J.; Park, K., *Reflexive Polymers and Hydrogels: Understanding and Designing Fast Responsive Polymeric Systems*. CRC Press: Boca Raton, **2004**.

[41] (a) Skvor, J.; Nezbeda, I., Percolation threshold parameters of fluids. *Physical Review E,* **2009**, *79* (4); (b) Callaway, D. S.; Newman, M. E.; Strogatz, S. H.; Watts, D. J., Network robustness and fragility: percolation on random graphs. *Phys. Rev. Lett.,* **2000**, *85* (25), 5468-5471.

[42] Fullerton, L. Programmable Magnets: Exploding Toys, Magnetic Puzzles, and Trick Magnets!! http://correlatedmagnetics.com/ (accessed October 24, 2010).

[43] (a) Zhou, J. F.; Meng, L. J.; Feng, X. L.; Zhang, X. K.; Lu, Q. H., One-pot synthesis of highly magnetically sensitive nanochains coated with a highly cross-linked and biocompatible polymer. *Angewandte Chemie-International Edition,* **2010**, *49* (45), 8476-8479; (b) Sun, J.; Tang, T.; Duan, J.; Xu, P. X.; Wang, Z.; Zhang, Y.; Wu, L.; Li, Y., Biocompatibility of bacterial magnetosomes: acute toxicity, immunotoxicity and cytotoxicity. *Nanotoxicology,* **2010**, *4* (3), 271-83.

[44] (a) Sanchez, C.; Arribart, H.; Madeleine, M., Biomimetism and bioinspirations as tools for the design of innovative materials and systems. *Nature Materials,* **2005**, *4*, 277-287; (b) Gebeshuber, I. C.; Gordon, R., Bioinspiration for tribological systems on the micro- and nanoscale: dynamic, mechanic, surface and structure related functions. *Micro and Nanosystems,* **2011**, (Special issue on Bioinspired Micro and Nanosystems), *3* (4), ???-???.

[45] Green, D. R., *Means to an End: Apoptosis and Other Cell Death Mechanisms*. Cold Spring Harbor Laboratory Press: Cold Spring Harbor, NY, USA, 2011.

[46] (a) Fox, H., Degeneration of tail notochord of *Rana temporaria* at metamorphic climax: examination by electron-microscopy. *Zeitschrift für Zellforschung und Mikroskopische Anatomie* **1973**, *138* (3), 371-386; (b) Sisto Daneo, L.; Corvetti, G.; Panattoni, G. L., Notochord degeneration in chick embryo: a particular case of developmental cell death? *Eur. J. Morphol.,* **1995**, *33* (5), 403-414.

[47] France, D. C., *Structure and Mechanics of the Spasmoneme, a Biological Spring within the Protozoan Vorticella convallaria [Ph.D. Thesis]*. Department of Biological Engineering, Massachusetts Institute of Technology: Cambridge, 2007.

[48] (a) Gilbert, J.; Punter, D., Release and dispersal of pollen from dwarf mistletoe on jack pine in Manitoba in relation to microclimate. *Can. J. For. Res.,* **1990**, *20*, 267-273; (b) Edwards, J.; Whitaker, D.; Klionsky, S.; Laskowski, M. J., Botany - A record-breaking pollen catapult. *Nature,* **2005**, *435* (7039), 164-164.

[49] Burrows, M., Energy storage and synchronisation of hind leg movements during jumping in planthopper insects (Hemiptera, Issidae). *Journal of Experimental Biology,* **2010**, *213* (3), 469-478.

[50] Beheshti, N.; McIntosh, A. C., A biomimetic study of the explosive discharge of the bombardier beetle. *International Journal of Design and Nature,* **2007**, *1* (1), 61-69.

[51] (a) Swaine, M. D.; Beer, T., Explosive seed dispersal in *Hura crepitans* L. (Euphorbiaceae). *New Phytologist,* **1977**, *78* (3), 695-708; (b) Swaine, M. D.; Dakubu, T.; Beer, T., Theory of explosively dispersed seeds - correction. *New Phytologist,* **1979**, *82* (3), 777-781; (c) Beer, T.; Swaine, M. D., Theory of explosively dispersed seeds. *New Phytologist,* **1977**, *78* (3), 681-694.

[52] Gordon, R., A retaliatory role for algal projectiles, with implications for the mechanochemistry of diatom gliding motility. *J. Theor. Biol.,* **1987**, *126*, 419-436.

[53] (a) Maschwitz, U.; Maschwitz, E., Platzende Arbeiterinnen: Eine neue Art der Feindabwehr bei sozialen Hautflüglern [Bursting workers: new means of defence in social Hymenoptera].

Oecologia, **1974**, *14* (3), 289-294; (b) Jones, T. H.; Clark, D. A.; Edwards, A. A.; Davidson, D. W.; Spande, T. F.; Snelling, R. R., The chemistry of exploding ants, *Camponotus* spp. (*cylindricus* complex). *J. Chem. Ecol.,* **2004**, *30* (8), 1479-1492.

[54] van den Broek, D. M.; Elwenspoek, M., Explosive micro-bubble actuator. *Sensors and Actuators A-Physical,* **2008**, *145*, 387-393.

[55] Ashmore, J., Cochlear outer hair cell motility. *Physiological Reviews,* **2008**, *88* (1), 173-210.

[56] Gosline, J.; Lillie, M.; Carrington, E.; Guerette, P.; Ortlepp, C.; Savage, K., Elastic proteins: biological roles and mechanical properties. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences,* **2002**, *357* (1418), 121-132.

[57] (a) Maniotis, A. J.; Bojanowski, K.; Ingber, D. E., Mechanical continuity and reversible chromosome disassembly within intact genomes removed from living cells. *J. Cell Biochem.,* **1997**, *65* (1), 114-130; (b) Burkert, J., *Critical Reflections on the Structural and Functional Models of Non-Random Chromosome Positioning Under Special Consideration of the Chromolinker Theory [Masters Thesis]*. Department of Medical Genetics, University of Glasgow: Glasgow, 2004.

[58] Gebeshuber, I. C.; Stachelberger, H.; Drack, M., Diatom bionanotribology-biological surfaces in relative motion: their design, friction, adhesion, lubrication and wear. *Journal of Nanoscience and Nanotechnology,* **2005**, *5* (1), 79-87.

Received: May 15, 2011 **Revised: August 16, 2011** **Accepted: August 20, 2011**

[59] (a) Schmid, A.-M. M., The "paradox'' diatom *Bacillaria paxillifer* (Bacillariophyta) revisited. *J. Phycol.,* **2007**, *43*, 139-155; (b) Jarosch, R., Zur Gleitbewegung der niederen Organismen [On the gliding movement of lower organisms] [German]. *Protoplasma* **1959**, *50*, 277-289; (c) Kapinga, M. R. M.; Gordon, R., Cell attachment in the motile colonial diatom *Bacillaria paxillifer*. *Diatom Research,* **1992**, *7* (2), 215-220; (d) Ussing, A. P.; Gordon, R.; Ector, L.; Buczkó, K.; Desnitski, A.; VanLandingham, S. L., The colonial diatom "*Bacillaria paradoxa*": chaotic gliding motility, Lindenmeyer model of colonial morphogenesis, and bibliography, with translation of O.F. Müller (1783), "About a peculiar being in the beach-water". *Diatom Monographs,* **2005**, *5*, 1-140.

[60] Zheng, J.; Shen, W. X.; He, D. Z. Z.; Kevin, B. L.; Madison, L. D.; Dallos, P., Prestin is the motor protein of cochlear outer hair cells. *Nature,* **2000**, *405* (6783), 149-155.

[61] Holmes, O. W., The Deacon's Masterpiece or, the Wonderful "One-hoss Shay": A Logical Story [Poem]. In *The Complete Poetical Works of Oliver Wendell Holmes*, S., H. E., Ed. Houghton, Mifflin: Boston, 1858; pp 158-60.

[62] de Jong, G. Tensegrity - Klein Bottle. http://beautifulcode.eu/tense-grity-klein/ (accessed July 17, 2011).