Tensegrity: The New Biomechanics

This is a rather long article that is a book chapter. It is fairly inclusive and brings a lot of the concepts expressed elsewhere into one article. It tried putting in as many links as possible to clarify particular points. If you read all the links, it becomes a book, not just a chapter. Good luck getting all the way through it.

Published In Hutson, M & Ellis, R (Eds.), Textbook of Musculoskeletal Medicine.
Oxford: Oxford University Press. 2006

The 'design' of plants and animals and of traditional artifacts did not just happen. As a rule both the shape and materials of any structure which has evolved over a long period of time in a competitive world represent an optimization with regard to the loads which it has to carry and to the financial or metabolic cost. **J.E. Gordon: Structures: or why things don't fall down. 303**

The anomalies

If we accept the precepts of most present day biomechanical engineers a 100 kg weight lifted by your average competitive weight lifter will tear his erector spinae muscle, rupture his discs, crush his vertebra and burst his blood vessels (Gracovetsky, 1988). Even the less daring sports person is at risk. A two kg fish dangling at the end of a three-meter fly rod exerts a compressive load of at least 120 kg on the lumbosacral junction. If we include the weight of the rod and the weight of the torso, arms and head the calculated load on the spine would easily exceed the critical load that would fracture the lumbar vertebrae of the average mature male. This would make fly fishing an exceedingly dangerous activity. Pounded by the forces of the runner striking the ground and the first metatarsal head acting as the hammer and the ground as the anvil the soft sesamoids would crush. A batter striking a baseball traveling at one hundred miles per hour, (160km/h), will be sheared from the ground, spikes and all. A hockey player, striking a puck will be propelled backwards on the near frictionless ice, as for every action there is an equal and opposite reaction.

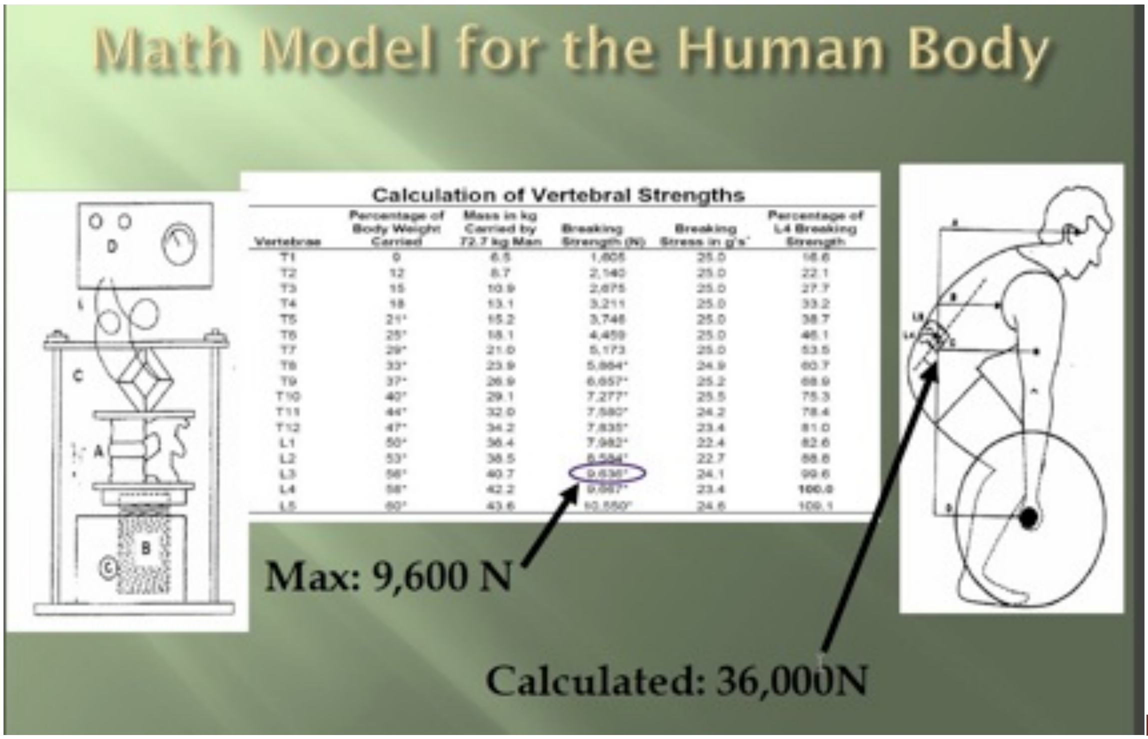

Fig. 1.
Competitive weightlifting is a mathematical absurdity. If we modeled the weightlifter using standard, Newtonian models, bones would crush and muscles would tear.

There is more to ponder. The brittleness of bones is about the same in a mouse as it is in an elephant, as the strength and stiffness of bones is about the same in all animals. Animals larger than a lion, for example horses, leaping on their slender limbs, would smash their bones with any leap (Gordon, 1988). According to the linear mechanical laws that dominate biomechanical thinking, animal mass must cube as their surface area squared and animals as large as an elephant will crush of their own weight. The large dinosaurs could never have existed, let alone be a dominant species for millions of years. Biologic tissues work elastically at strains that are about a thousand times higher than strains that ordinary technological solids can withstand. If they behaved as most non-biologic materials, with each heartbeat the skull should explode as the blood vessels expand and crowd out the brain and urinary bladders should thin and burst as they full. The pregnant uterus should burst with the contractions of delivery.

Not only mechanical but also physiologic processes would be inconsistent with linear physics. Pressure within a balloon decreases as it empties. Following the same physics the systolic pressure should decrease as the heart empties, it, of course, increases. We could never get the air out of our lungs or empty our bladders or bowels. If we functioned as columns and levers, our center of gravity is too high and our base is too small and weak for ordinary activities. When swinging an ax, sledgehammer, golf club or fishing rod our center of gravity would fall outside our base and topple us over. We could not lift a shovel full of dirt. The calcaneus is a very soft bone. Our heels should crush from the super incumbent load and could not sustain the load of a gymnast coming off a high bar. The 'iron cross' position, [fig 2] attainable by any competent gymnast, would tear him limb from limb unless he defied the cosine law taught in every basic physics course which, in effect, states that the forces pulling on a rope strung between two poles becomes infinite as the rope becomes straight.

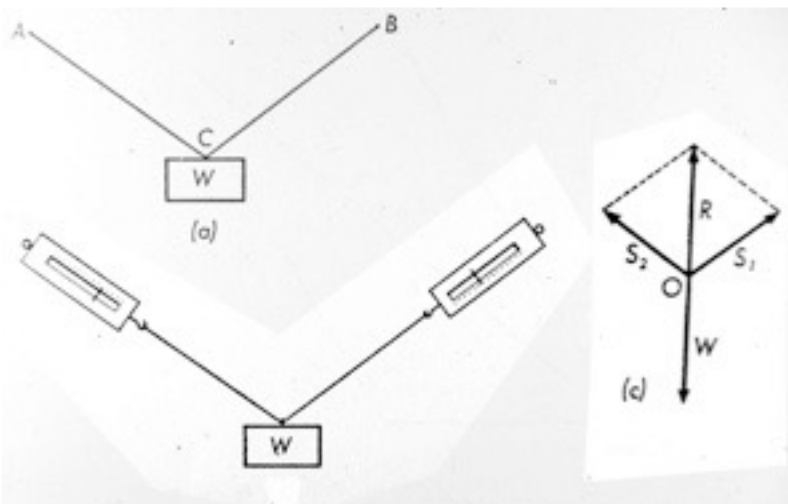

FIG. 2-2. Forces exerted by strings in supporting a weight.

Fig. 2. Following the **cosine law**, as the string AB becomes straight, the vector (c) becomes infinite. Applying that principle to the 'Iron Cross', creates another mathematical absurdity.

When confronted by these anomalies biomechanical engineers either ignore the problem or go to great and circuitous lengths to try to justify the results. However, these explanations rarely stand the test of scientific scrutiny, or even good sense. According to bioengineers, living organisms are modeled like skyscrapers (Schultz, 1983). There are serious inconsistencies that test the model. The base of a skyscraper is always stronger than its top. It is dependent on gravity to hold it together. It cannot be flipped over or even tilted very far as the internal shear created would tear it apart. Its joints must be rigidly welded. Biologic hinges are freely moving, not rigidly welded. We are not constructed like skyscrapers with our base firmly and forever rooted to the ground and held in place by the force of gravity. Animals balance on flimsy supports. How does a flamingo leg, a long, thin strut, with a near frictionless hinge in the middle, hold up a flamingo? [Fig. 3 A] Most biologic organisms that are upright, including plants, have their top half heavier than their base. Stone walls and skyscrapers, but not flamingos, are, necessarily, thicker at their base. If our center of gravity falls outside our base we are not torn apart by internal shear forces as happens to columns of stone [Fig. 3 B&C]. Biologic structures exist independent of gravity. They are omni-directional structures that can exist and adapt to water, land, air and space.

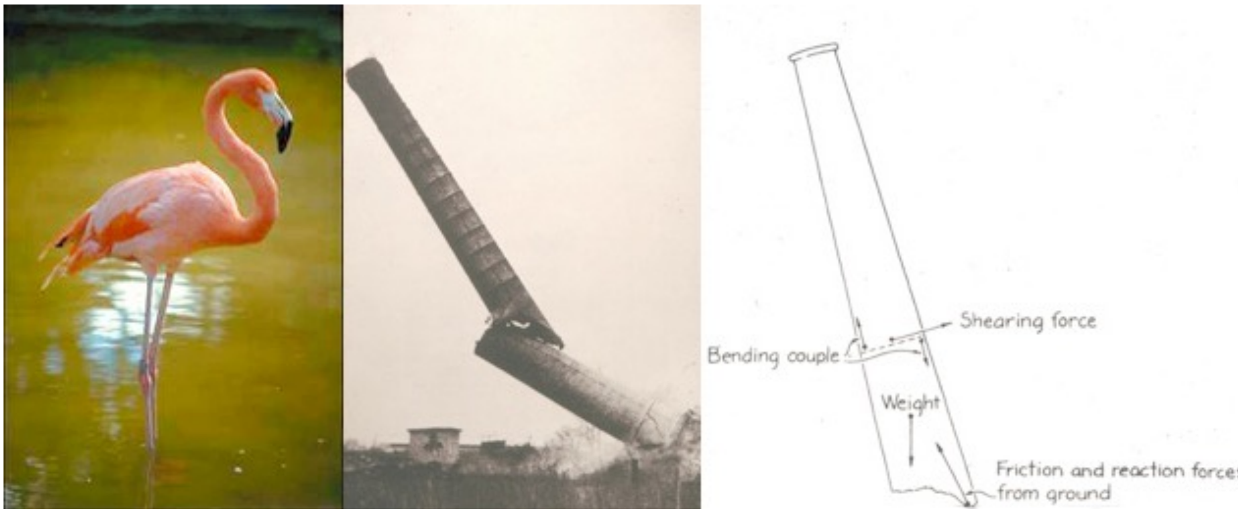

Fig. 3. A. Note the absence of tissue mass that would be necessary to support the flamingo's 'knees' (actually, ankles). B.& C. A falling column creates **shear** and will fracture before it hits the ground.

The Evolution of Structure

Certainly, no natural laws are broken. It is just that bioengineers usually consider only Newtonian mechanics as their basis for calculations. Biologic materials are non-Hookean and non-Newtonian behaving physical structures and we cannot use **Hookean** and Newtonian laws to understand the material behavior of biologic organisms. Hookean and **Newtonian** materials behave in a linear, additive fashion. Biologic materials behave non-linearly or non-additive and are not predictable using Hookean and Newtonian mechanics (Gordon, 1978). As pointed out by Gould (Gould, 1989) the combined action of any the parts yields something other than the sum of the parts and there is emergence of new properties or synergies. What is clearly needed is a new model to replace the post and beam, column and lever, Hookean and Newtonian model that now dominates the thinking of biomechanics.

The military maxim of 'never stand when you can sit, never sit when you can lie down, never stay awake when you can be asleep' applies to nature's ways. Evolution is an exercise in optimization. The least energy requiring solution will eventually happen and once it happens that solution will become the norm. Nature has a predilection for using and reusing whatever works and works with the least amount of energy expenditure. Patterns and shapes in nature will evolve to their fittest form

(Stevens, 1974) with the tightest fit, and least energy expenditure. Nature also functions in a 'minimum inventory maximum diversity' mode trying to make do with the least amount of basic material, to gain the maximum effect (Pearce, 1978). DNA is constructed with just four nucleic acids and most of the DNA material of a lowly worm is similarly repeated in the human genome. These genes are then used as templates to construct larger proteins and larger proteins add to other proteins and so on.

The development of biological structure, whether organelles packed in a cell, cells packed in tissues, tissues packed in organs or organs packed in organisms is always in a **'closest packed'** environment. [Fig. 4] The same is true of fish eggs in water, bee eggs in a hive, embryos in eggs, and fetuses in utero. Structural evolution of biologic organisms will therefore obey the physical laws of 'triangulation' and 'closest packing' that are the physical laws that apply to structures filling space such as soap bubbles, grains of sand on a beech, oranges in a crate, molecules of water in a drop or boulders on a mountain. The laws of closest packing are a subset of Newton's third law, for every action there is an equal and opposite reaction. If you step on a concrete floor the area beneath your foot 'gives', infinitesimally, but exactly equal to the load of the weight applied. In closest packing there is a balance of the external forces of molecules, sand grains, droplets, cells or whatever crowding each other and the internal forces of the structure being crowded pushing out to keep from being crushed. This balance of forces assumes the least energy consuming relationships.

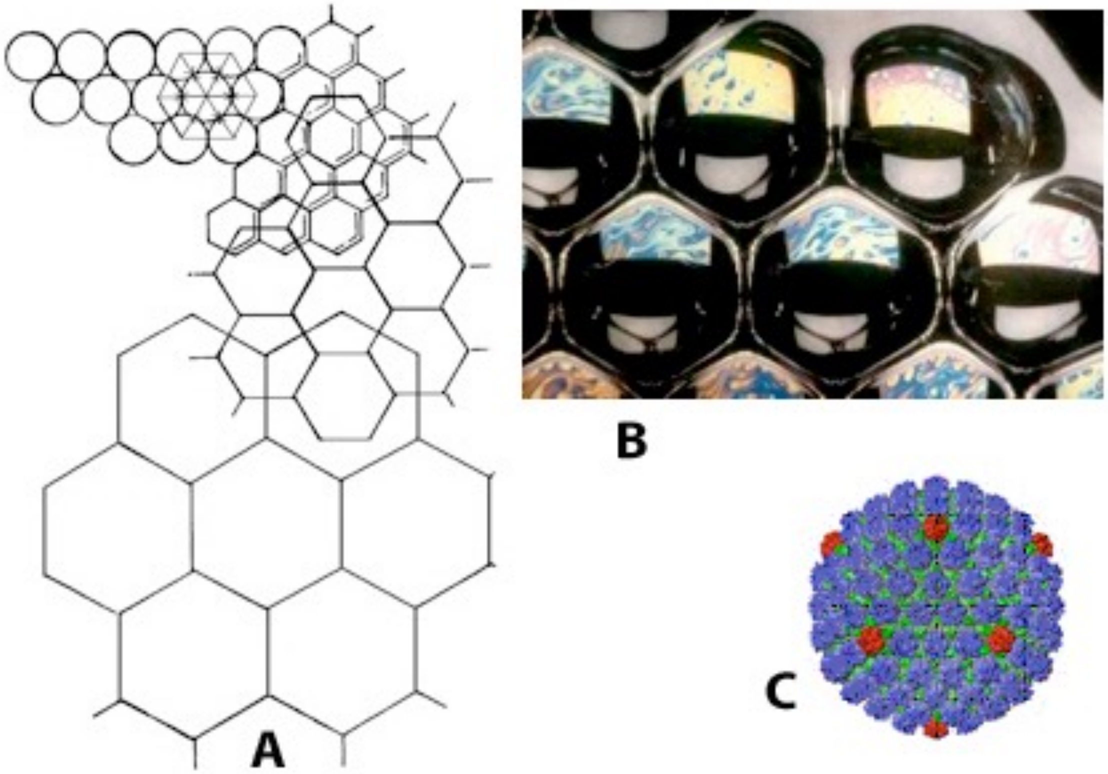

Fig. 4. Hierarchical close packing,exemplifies by (B) oil bubbles and (C) proteins in a virus capsid.

The developing mammalian fetus is initially adapting to the closest packed compressive forces in utero. Biologic tissue adapts to the forces applied by getting stronger and developing specialized structures and tissues to resist those forces (Wolff, 1892) (Carter, 1991). [Fig. 5]

Fig. 5. Wolff's Law in bone. The denser bone is laid down where the compression stress is greatest. Conversely, the softest bone is where there is the least compressive load. Therefore, by examining bone density it is possible to determine what bone takes the most stress, and which the least. For example, the calcaneus and the metaphyseal ends of long bones take little compressive loads.

It is remarkable that the fetus, developing to resist the omni-directional pressure within the uterus, can then resist the asymmetrical and very high compressive forces of delivery through the birth canal and then instantly adapt to a completely new environment. Initially adapting to and balancing compressive forces from without so as not to get crushed, it now has to resist the expanding forces from within without exploding. With each heartbeat and breath, the newborn should blow up like a balloon. The newborn is not a wineskin taking its shape from the unconstrained and unorganized fluid within and neither are any cells that maintain their shape, closest packed, within the structure or completely removed to an open space environment. The outer container, the skin, does not contain the contents like the walls of a cylinder, but the restraint of the explosive forces within come from deep within the structure itself. The same is true of cells, tissues, and organs. The chondrocyte has to balance the internal pressures with its external loads; otherwise, it would crush or explode. The chondrocytes in the knee joint must be contained when unloaded but instantly able to withstand the crushing loads of a fullback running down the field. Cartilage tensile strength is thirty times weaker than bone, muscle tensile strength one thousand times weaker than tendon. Cartilage should shear right off the bone and muscles should tear with only minimal tendon pulls unless the loads are distributed through the tissues. We know, from Darwinian theory and **Wolff's law**, that cartilage and muscle are as strong as they need be. There must be some distribution and dispersing of loads in biologic structures. From sub cellular to cellular to tissue to organ to organism, there is a hierarchy of individual closest packed structures that are interdependent of and, at the same time, independent of one another. These structures must evolve consistent with Darwinian concepts and must be self-generating, omnidirectional, independent of gravity, and least energy consuming structures.

To understand the evolution of biologic structures we must understand how nature fills space. Two-dimensional space filling is an exercise in triangulationThe triangle is the simplest and the most stable and least energy-requiring polygon. It will not deform even with flexible corners (vertices) as long as the sides remain connected, straight and at the same length. Square frame constructs are unstable and will deform into a parallelogram and eventually flatten to a pancake [fig. 6].

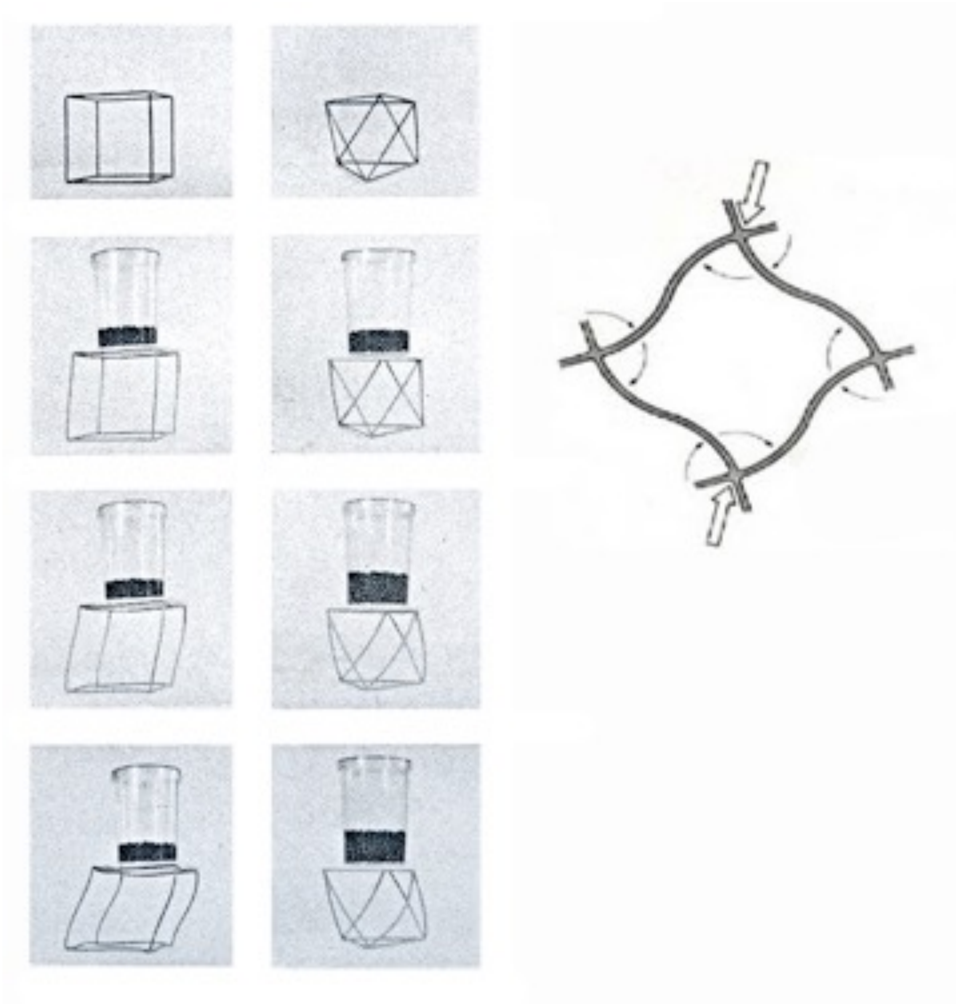

Fig. 6. The unstable square frame. Any structure that is not triangulated is inherently unstable and would require its joints to be fused to keep from collapsing. Torque and moments are created at the joints.

They require rigidly fixed corners to maintain themselves. If a structure exists with all its joints flexible, then it must be fully triangulated. When we pack six equilateral triangles arranged around a point in a plane it forms a hexagon and closest packed hierarchical arrays of triangles in self-generating hexagons fill a planar space [fig. 4A]. This is the least energy requiring arrangement of structure in two-dimensional space, familiar as the cross section of a beehive. Hexagons, however, will not enclose three-dimensional space. In the three dimensional world in which we live pentagons and hexagons are mathematical concepts with only two dimensions. To give them three dimensions they can only exist as part of some stable three dimensional structure, a tetrahedron, octahedron or icosahedron which are the only fully triangulated regular polyhedrons [fig. 7].

Fig. 7. The three symmetric and physically stable polyhedra.

To do that the geometry changes a bit. Five equilateral triangles will form a bowl with its perimeter a pentagon. When you continue to add triangles in a closest packed environment, they curve back on it and becomes a hollow closed space (Hargittai, 1992), [fig. 8].

Fig. 8. Space filling with triangles. Six triangles create hexagons and create a planar array (fig,. 4A). Five triangles will create a cupped pentagon and close packing pentagons will eventually enclose space. Closed space is defined by twelve pentagons, no more, no less.

Twenty planar triangles fit together as an icosahedron perfectly enclosing the space. This configuration, too, has self-generating properties. This is one of the **platonic regular convex polyhedrons**,

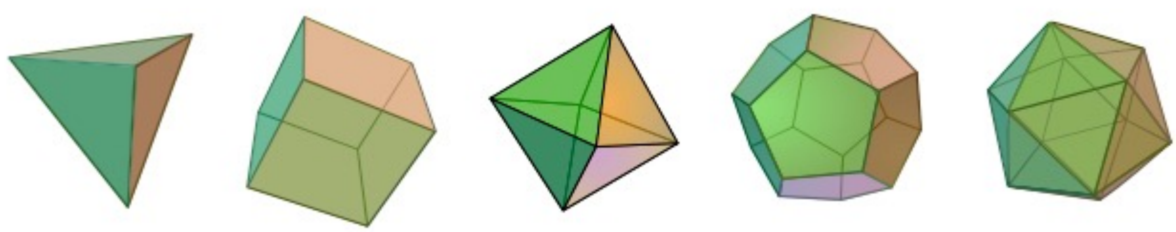

Fig. 9. The platonic polyhedra.

there are only five, and all convex polyhedrons are some combination, permutation, or higher frequency of these five basic polyhedrons. They were known to the Greeks and other early mathematicians and there are no others. Only three of the five are fully triangulated and, therefore, least energy structures (Fig. 7). They are the tetrahedron with four sides, the octahedron with eight sides, and the icosahedron with twenty sides. Water molecules, silicone molecules, carbon molecules and methane gas molecules are all tetrahedrons. Twelve pentagon faces will enclose space as a duo decahedron. However, duo decahedrons are unstable frames structurally, as is the cube. Using hexagonal (cube) modeling for finite element analysis would not reflect the structural integrity of the tissue, tetrahedral modeling is more consistent with the way biologic structure forms and behaves. Filling the interiors of the hollow polyhedrons must follow the same closest packing laws. Closest packing twenty tetrahedrons around a point in three-dimensional space will create an icosahedron just as six triangles created a two dimensional hexagon.

Icosahedrons have threefold, fivefold and six fold symmetry, depending on how you slice it (Hargittai and Hargittai, 1994) [Fig.10.].

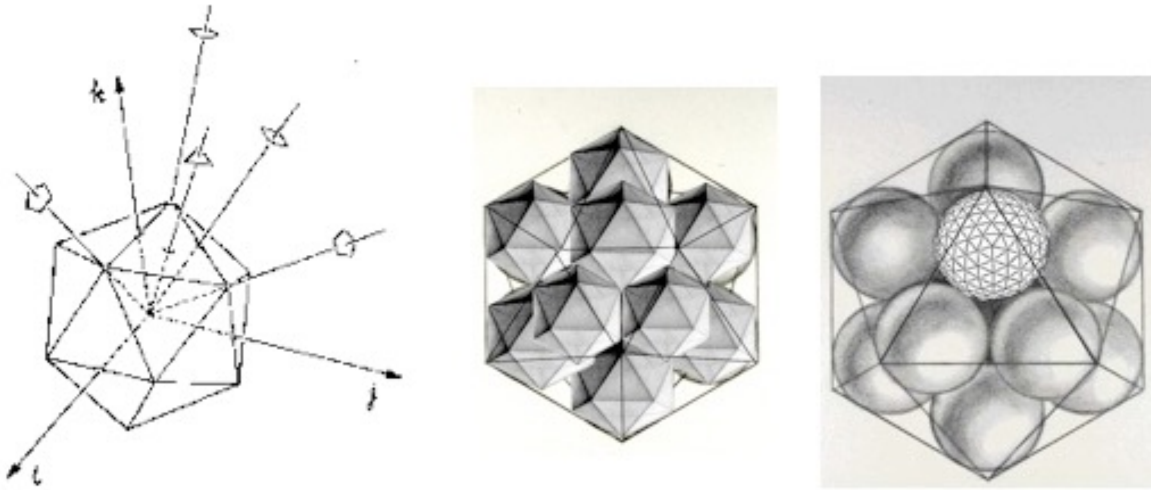

Fig. 10. Symmetries and close packing of icosahedrons.

There are twenty triangular, threefold faces, five fivefold, slightly cup shape pentagons on a thicker slice and, on thick cross section, its mirror symmetry, a six fold hexagon cup, casting a hexagonal shadow. Twelve equal size icosahedrons closest pack to form sphere, joining at their five fold symmetry (pentagon) edges. The center is a hollow, somewhat smaller, icosahedral shaped vacuole. Six fold relationships will create, stable in two dimensions but unstable in three dimensions, sheets of icosahedrons. Combining fivefold and six fold symmetries a variety of saddles, tubules and hemispheres are created. A combination of twelve pentagons, interspaced with hexagons, will enclose any space. Icosahedrons combining in fivefold symmetries and six fold symmetries will likewise enclose any space. Joining at threefold symmetry faces the icosahedrons cannot fit. They will stack on another to create helixes [fig. 11].

Fig. 11. Stacking Icosahedrons on their threefold symmetry faces creates helices. Kroto describes this phenomenon at the nano particle, naming them “icospirals”.

As **fractals** (Mandelbrot, 1983), sharing faces and edges and intersecting one another, just as soap bubbles do, they will form an infinite array of inter linked, hierarchical, stable structures functioning as a whole or as sub sets of icosahedrons [fig. 12].

Fig. 12. Tensegrities as fractals. Just as bubbles coalesce and share structural components to form a a bubble mass, tensegrities can coalesce to form a single mass that functions as one tensegrity.

Biotensegrity

As you can see, the icosahedron has many things going for it. It is mathematically the most symmetrical structure and is omni directional in form and function. It has the largest volume for surface area of the regular polyhedra and larger structures are only higher frequency Icosahedrons. The icosahedron has thirty edges and twelve vertices with twenty sides. If the edges are rigid, then pressure at any point transmits around the thirty edges putting some under pressure and others under tension, in a regular pattern. The twelve vertices each have three edges that come together at that corner. Some of these edges are under tension and some under compression, depending on the vector of force applied to the structure. The compression load can be transferred away from the outside of the structure by connecting the vertices opposite to one another by rigid compression bearing rods. These rods do not pass through the center of the icosahedron but are slightly eccentric and pass each other without touching [fig. 13]. These compression rods are now joined at the icosahedral vertices by a continuous tension shell with all the edges on the outside of the icosahedron under tension, the 'tensegrity' icosahedron.

a
b
c

Fig. 13. A. An 'exoskeletal' icosahedron, with the compression elements in the outer shell. B. An 'endoskeletal' icosahedron, the compression rods 'float' within the tension network creating a **space frame**. C. Transformation.

Tensegrity, a word coined by Buckminster Fuller (Fuller, 1975) to describe continuous tension discontinuous compression structures, was applied to constructs designed by Kenneth Snelson (Snelson, 2002) and Fuller. Examples of these structures are Snelson's Needle sculpture at the Hirshhorn Museum, Washington DC [fig. 14A], and Fullers now ubiquitous geodesic domes [fig. 14B] and the wire cycle wheel.

Fig. 14. A **Needle Tower 1964 (Snelson K.)**, Hirshhorn Museum, Washington, DC. B. Example of a geodesic dome. Epcot Center, Disneyland, FL.

Biotensegrity is the application of tensegrity principles to biologic structures. The tension or tensegrity icosahedron, is a pre stressed, semi-rigid structure constructed of tension and compression members where none of the compression units compressing each other. They 'float' within the tension outer skin. Just as the single icosahedron can have either an **exo** or **endo skeleton** [Fig. 13, 14] the linked, hierarchical structure can internalize its compression components and the whole structure can behave as a single icosahedron. As you can see, what happens is that a hierarchy of icosahedrons creates itself balancing the external forces and internal forces as a self-generating structure.

The wire spoke bicycle wheel is the most common easily recognizable non-biologic tensegrity structure. The mechanics of a wagon wheel and a bicycle wheel are completely different [fig. 15].

Fig. 15. The hub of a wire wheel is suspended in a tension network. The axle load is hung from the top of the rim that tries to belly out. Additional tension spokes are added horizontally to resist the bulge. For circumferential stability, the additional spokes are added. (After Fuller]

A wagon wheel [Fig. 16] transmits the wagonload to the ground through the axial compressing the spoke between it and the ground. The spoke has to be strong enough to withstand the full weight of the wagon; it gets no help from the other spokes, which, at that moment, sustain no load. Besides the **compressive** loads, internal **shear** is created within the spoke.

Fig. 16. Wagon wheels vault from spoke to spoke. When loaded each spoke acts as a column with compression and shear. BCD. Compression in a column creates shear stress. Therefore, the column must be thick, stiff and and strong.

The intervening rim acts as the pedestal of the columnar spoke and has to be equal to the task of being crushed by the full weight of the wagonload. As the wheel rotates it vaults from spoke to spoke. Halfway through the transfer of compressive load from one spoke to the next the rigid rim acts as a **lever**, creates **bending moments**, and has to be strong enough to withstand the additional loads. At any one instant in time, the structures are locally loaded and the remaining elements can be stripped away without seriously compromising the structural integrity. (The wheel just could not role on.) In a bicycle wheel, the hub is suspended, hanging from the topmost spoke [Fig.15]. This would cause the thin, weak rim to **buckle**. It is kept from buckling by the other wire spokes constantly pulling in on the rim to keep it round. All the spokes are under constant and equal tension. The tensions are preset and do not vary with the load. It is an integrated structure with each spoke depending on every other to share the load at all times. The compression of the ground to the rim is distributed through the tension spokes to the hub. Therefore, there is no direct compression link between the load on the bicycle frame and the **ground reaction force**. The bicycle is suspended off the ground in a tension spoke network, hanging like a hammock, and the same system works equally well in a unicycle as a bicycle or tricycle. In a cycle wheel, the hub and rim are compression elements kept apart by tension spokes. There are no bending moments in the tension spokes, which are pre stressed, under constant tension. The cycle wheel exists only as an integrated structure. One spoke will not hold up under the weight of the load.

Once constructed this way the tension elements remain in tension and compression elements remain under compression no matter the direction of force or point of application of the load. It makes no difference where you compress the rim of the cycle wheel; the load is equally distributed through the spokes to the hub. The rim of the bicycle is a geodesic, connecting the many points of the spoke attachments, the more spokes the rounder it gets. If the narrow rim is expanded to a sphere by creating great circle bands around the hub then the outer, exoskeleton of the geodesic-sphere is rigidly fixed to the central hub and transmits load to or away from that hub by the tension spokes [Fig. 17].

Fig. 17. A. London Eye - A very large tension wheel structure. B. Tensegrity wheel within a wheel. The rim is a tensegrity torus and the hub a tensegrity icosahedron. (Flemons 2007)

As already noted [Fig.13], in some tensegrity structures the compression elements can be internalized and the tension elements externalized to create an endoskeleton using the same mechanics with the outer skin under tension and the inner skeleton intertwined in the tension network. The structure is truly omni directional. It never has to change tension elements to compression elements, or visa versa, to resist the compressive forces from without or the explosive forces from within, no mater from which direction the load is applied. Loads applied to the surface of linear, Hookean structures create a dimple right under it and the whole structure starts to squash flat. Loads applied to a point on the skin of a tensegrity icosahedron are distributed evenly around all the edges in tension and across the floating rods under compression. Since load applied to the surface is distributed uniformly over the entire surface, instead of flattening and spreading out, the tension icosahedron uniformly becomes smaller and more compact with the compression rods approximating each other more closely. The internal pressure of the icosahedron increases as at becomes more compressed and it does so as a factor of the square of the radius. This relationship when graphed is as a 'J' curve [fig.18] that represents a nonlinear stress strain relationship.

Fig. 18. Linear and nonlinear Stress/Strain curves. Note the intrinsic tension in the Nonlinear S/s. The curve never get to zero stress even in its most 'relaxed' state.

This is radically different from the **Hookean**, linear behavior of most non-biologic materials and structures. In Hookean structures for each increment of stress, there is a proportional strain until the point of elastic deformation just before it breaks. Hookean structures weaken under load. In the tensegrity structures, there is rapid deformation with the initial load but then the structure stiffens and becomes more rigid and stronger. This 'J' shaped nonlinear curve is also a characteristic response of biologic tissues from cells to spines. Tug on your lip and you will note that as you tug the skin is loose at first and then becomes stiffer and effects larger and larger areas of skin. The cells under the heel could not sustain crushing loads of the runner without this type of elasticity, as they would burst. This behavior not only is of the skin but also then connects deeper eventually reaching right down to the bone. The process is reversed when any pressure is applied to the skin, as through the sole of the foot, with the soft tissues resisting the compressive force by tension, just as does the wire spoke and then distributing through the compressive bearing bones.

The importance of the J shaped non-linear response of biologic tissue and the difference between the soft tissue mechanics of biologic materials and structures cannot be overemphasized. The rigid materials used in non-biologic constructs generally operate at elastic strains in the region of 0.1 percent. Rarely they may strain, that is deform to the point to which they can fully recover, ten times that amount. Conceivably, they can go to elastic strains of 20 percent but at that level Hookean material reaches the level when its chemical bonds would explode with the force equivalent to an equal weight of an explosive. Biologic tissues commonly operate at strains of 50 to 100 percent or more, often 1000 times greater than those of conventional engineering materials do [Fig 19A].

a
b
Fig. 19. The elastic strain of biologic tissue far exceeds that of most structural materials, nor does it resemble rubber. What would happen if you extended bladder would burst like s a balloon.

Neither does it behave as rubber does [Fig. 19B], which has an S shaped stress-strain curve and is characterized by bursting at its elastic limit and aneurysm formation which would not do well in arteries. The elastic behavior of biologic tissue when initially stressed behaves almost like the surface of a liquid at low and moderate strains. It then rises in its very characteristic, non-Hookean, 'J' response. Mathematically, this is the only sort of elasticity that is completely stable under the fluid pressures at high strains found in blood vessels, alveoli, bladders, bowels, muscles, uteri and most other biologic soft tissues (Gordon, 1978). The properties imparted by this curve are flexible and tough. With this configuration, it is biologic tissue unlikely to fracture, explode or be prone to aneurysm formation. Tendons and bone can store large amounts of energy and return it like a spring in leaps and bounds.

The model usually used to approximate this type of behavior is the so-called 'visco-elastic' behavior of biologic tissues. This is a complicated and rather contrived behavior that puts the response of a Hookean elastic material parallel with the response of a **Newtonian**

a
b
c
Fig. 20. A and B. Hooke's Law and Hookean behavior of a spring. C. Non-Hookean spring and dashpot, the model for visco-elastic behavior of biologic tissues.

behaving fluid and those, then, in series with another Hookean body [Fig. 20]. Modeling life's behavior would be simplified if there were a naturally occurring structure, such as the tensegrity icosahedron that does have these characteristics, that nature can use for its constructs.

Biologic tissues are pre stressed with the 'J' curve never zeroing out so that there is always a balance of dynamical forces acting on the structure. Often compression and tension roles can be reversed in these types of structures but the sum function may remain the same. To appreciate these qualities consider a pneumatic tire or a balloon, which are also **pre-stressed** structures. The walls of the pneumatic structures are prevented from collapsing by the collision of molecules of gas within it pushing on all surfaces equally. The pressure in a tire is the same whether the car is up on a lift or sitting on the ground. (I have won a fair amount of money betting on this). Sitting there the tire seems a little flat. To get a more efficient roll you can put in more air or heat up the gas inside the tire creating more energy in the tire and more collisions of molecules on the walls. The friction on the road does just that. It is the balance of the internal energy of the gas and the external elastic energy of the tire wall, which is under tension that defines its functional capabilities. It reacts to its load but is not dependent on it. In a wire spoke wheel the spokes pull the rim toward the center rather than push out, as do the molecules of gas in a pneumatic tire. Until an adequate number of spokes are properly placed, the spokes cannot be tightened. Once at that point, (the minimum number is twelve), the wire wheel behaves as the pneumatic tire does, only in reverse. Instead of the gas molecules pushing out the spokes pull the rim toward the center, the tension is inside and the compression is outside. This shows how the tension and compression elements can be reversed but still perform similar functions.

Over the years, Levin (Levin, 1982; Levin, 1986; Levin, 1995; Levin, 1997) and others (Wildy and Home, 1963; Ingber and Jamieson, 1985; Wang, Butler, and Ingber, 1993; Stamenovic et al., 1996; Ingber, 1997, 2000; Wang et al., 2001) have proposed a new model for biologic structures based on the concept of tensegrity. In vertebrates the skeleton would be compression elements within a highly organized soft tissue construct rather than the frame supporting an amorphous soft tissue mass. The same organization occurs at the cellular level with the cytoskeleton and the, anything but amorphous, cytoplasm. Tensegrity structures are omni-directional, independent of gravity, load distributing and energy efficient, hierarchical and self-generating. They are also ubiquitous in nature, once you know what to look for. They can be used to model biologic structures, from viruses to vertebrates and their systems and sub systems. They are fully triangulated and therefore, least energy systems, that are stable even with flexible hinges. The tensegrity icosahedron can be linked in an infinite array in hierarchical systems and fractal constructs that can function together in unison acting as an icosahedron no mater what its shape. It can be considered the finite structural element and used as a building block for all biologic structures. Its non-linear stress-strain curve is a characteristic and even defines biologic tissues (Gordon, 1988). The tensegrity model is now gaining wide acceptance as a model for biologic mechanics (**Ingber**, 1998) and is very useful in understanding the mechanisms of action in orthopedic medicine.

The Shoulder Modeled as a Biotensegrity Structure

The principal of tensegrity modeling can be well demonstrated in the shoulder, which is the least successfully modeled joint complex using Newtonian mechanics. In multi segmented mathematical shoulder models, rigid beams (the bones) act as a series of columns or levers to transmit forces or loads to the axial skeleton. Forces passing through the almost frictionless joints must, somehow, always be directed perfectly perpendicular to the joints as only loads directed at right angles to the surfaces could transfer across frictionless joints (**Levin**). Loads transmitted to the axial skeleton would have to pass through the moving ribs or the weak jointed clavicle and then through the ribs. As the arm circumducts in any plane, it inscribes the rim of an imaginary wheel (fig. 21).

Fig. 21. The arm visualized as the spoke of a wheel.

The arm becomes the spoke that transfers the load at the hand to the axial skeleton. Present models conceptualize the upper extremity as a wagon wheel spoke. In a wagon wheel model, loads are transferred by connected rigid compressive columns or beams, the spokes (fig. 16).This is a classic Newtonian construction with columns, beams, levers and fulcrums with resulting bending moments and torque. The bones of the arm are envisioned as the rigid spokes but although there is a bony articulation at the glenohumeral joint that might be able to transfer compressive loads from the arm to the scapula there is no rigid, compressive load bearing structure between the scapula and the axial skeleton, nor is there a suitable fulcrum [Fig. 22,23,24]. In a linked lever system a seamless continuum of compression elements are necessary. Bone must compress bone. The almost **frictionless joints** would require forces to be always directed at right angles to the joint. The scapula is not anatomically situated to transfer loads through the ribs to the spine. Even if it were, the ribs could not take these loads and act as levers to connect to the spine. [**The Slippery Slope]**

The ribs themselves, by shape, position and connection, are not structurally capable of transferring these loads. The clavicle is in no shape to transfer loads, either. It is a crank shaped beam that connects the scapula to the sternum by a small, mobile joint that could not transfer compressive loads of any significant magnitude [Fig.23A]. Cats [Fig.22A] do not have articulating clavicles and they can run and climb with the best of us creatures. The scapula of quadrupeds and bipeds hangs on the thorax (Fig. 22) by a network of muscles and all the moment and compression forces generated in the arm must be transferred to the axial skeleton through these soft tissues [Fig.23ABC] [**The Scapula is a Sesamoid Bone**].

Fig 22. In quadrupeds, the scapula is easily visualized as the topmost part of the 'tower' of a suspension bridge, with the spine equated to the roadbed suspended under the towers. It is clear that the scapula and the spine are linked by tension, not compression.

A rope cannot withstand compressive loads nor can it function as a lever and neither can muscle or tendon. A wagon wheel, which depends on rigid, compressive load bearing spokes to transfer, loads and is not a suitable analogy for shoulder girdle mechanics.

Fig 23. The 'floating bones' (A) are enmeshed in a network of muscles, much as the hub of a bicycle wheel is enmeshed in its tensioned spokes (BCD).

If we use a wire cycle wheel tensegrity structure as our model the shoulder is readily modeled and takes into account all the necessary factors in joint modeling. If we consider the scapula functioning as the hub of a tensegrity structure then the forces coming from the spoke-like arm could be transferred to the axial skeleton through the soft tissues rather than the circuitous and imposing linked levers of the bones.

Fig 24. Floating bones as they be conceived as compression and tension members of a tensegrity icosahedron. The whole structure would realign with changes on position, creating a new tensegrity relationship.

A bicycle wheel - tensegrity model is mechanically more efficient than a spoked wagon wheel model. In a wagon wheel, only one or two spokes are sustaining loads at any one time. The spoke must be rigid and strong enough to withstand the entire weight thrust upon it. It gets no help from its neighbors. The rim of the wagon wheel must also be strong enough to withstand these crushing loads directly at the point of contact with the road. In a wire wheel forces are distributed, all the elements act in concert and all the spokes contribute all the time. The rim is part of the system and the compressive load, directed at a point, is taken by the entire rim. Tensegrity structures are fully triangulated and, therefore, there are no bending moments in these structures, just tension and compression and therefore significantly less loads to be reckoned with. Tensegrity structures are omni directional load distributors. The tension elements always remain in tension and the compression elements always remain in tension no matter in what direction the loads are applied. This is not so in a column or a lever which are rigidly oriented to resist a load from a specific direction. Because the loads in tensegrity structure are distributed all the time, each structural element can be lighter.

Grant (Grant, 1954) used a tension model to suspend the body, hammock like, when it hangs between gymnastic parallel bars.

Fig 25. The 'suspension bridge' model for biped arms. There is no need to have a separate mechanical model for quadruped (fig. 22) forelimbs and biped forelimbs. (Grant)

However, hammock like suspension is unidirectional. Turn the hammock or suspension bridge over and, not only does everything fall out of the hammock or off the roadbed, the hammock or roadbed also collapses. For a similar reason, a boat mast is not a suitable model for biologic structures. Buildings, boats and bridges have 'sense', an orientation in space, for structural integrity as well as function.

Fig 26. 'Mast' or 'tower' (Fig. 22) models, are unidirectional and depend on a stable base for support. They are not self-contained, omnidirectional structural entities.

If a tensegrity structure is omni directional inform and function and can be used right side up, upside down or any position in between and still maintain its form, structural integrity and its ability to transmit loads. When modeling a shoulder as a tensegrity structure the bones that 'float' in the tension network of soft tissue are only being compressed. There are no moments at the joints because the structure is fully triangulated. In this model the shoulder becomes inherently stable and changes position only when one of the elements of the triangle is shortened or lengthened, just as changing the tension in a wire spoke will distort the wheel. The continuous tension present in the soft tissues stabilizes the joints at each moment. Therefore, considerably less energy is needed to 'stabilize' the joints.

The scapula, suspended in the 'spokes' of the attached muscles and soft tissue, could function as a stable base for the arm. It could also transfer loads to the 'rim' of vertebrae through these same spokes. With the scapula as a hub in a tensegrity system loads are transferred from the arm to the spine through the large amount of available muscle and ligaments through a stable yet easily mobilized, omni directional, low energy requiring system that would utilize lighter, less bulky parts and accommodates global motion and stability. This contrasts with a multi-segmented articulated column model that is inherently unstable and has high-energy requirements. In multi-segmented systems, with each change of direction of load, new mechanics must be established. The tensegrity model is readily visualized when modeling scapula mechanics, since there are really no suitable compressive load-bearing joints that can connect the scapula to the spine.

Fig 27. The omnidirectional shoulder girdle works under compression or in tension, and can rapidly shift from one mode to the next. It can transmit forces and be remarkablyMobile, flexible, and instantly stable under a wide range of conditions and directions.

Muscles, as well as all other soft tissue elements in the body, are always under some tension, they are pre stressed. It is the tone of the muscle that holds us upright, keeps our jaw from dropping and our scapulas from sliding off our chest wall, as we do these things when the EMGs are electrically silent (meaning there is no active contraction of the muscles. The tone of the muscles and the stored elastic energy in the soft tissues must be reckoned with as stabilizers and as motors to understand the forces that control stability and mobility in the body. The transfer of forces in the body could possibly be through these already tense soft tissue elements. (**Muscles at Rest**)

The glenohumeral articulation may appear, at first, to be a more traditional compressive load bearing joint. But, for the joint to be stable forces must be directed at right angles (normal) to the joint since the cartilaginous surfaces are essentially frictionless. The glenohumeral joint is a multi-axial ball-and-socket joint. The head of the humerus is larger than the glenoid fossa and the surfaces are incongruous ovals and not true spheres. There is no bony structural stability and the joint is loosely packed with a great deal of play between the surfaces. There are very few positions of the arm in which the humeral head directs its compressive forces normal to the glenoid fossa. Usually the forces are directed almost parallel to the joint surface. Since there is a change in direction of forces, in order to transfer forces to the scapula to glenohumeral joint must function much like the universal joint of an automobile drive shaft. As Fuller points out, universal joints are analogous to the wire wheel as a basic tensegrity system. It relies a on the differentiation of tension and compression for its effectiveness. The soft tissues, the capsule, ligaments and muscles act as the connecting pins of a universal joint. Both the scapulothoracic and the glenohumeral joints may be modeled, efficiently and easily, as tensegrity structured joints. As a rigid, multi- segmented lever, modeling the shoulder is a struggle.

Fig. 28. The dynamics of a loosely-packed shoulder in motion.

Motion

Movement is an integral part of animal life and even the strongest trees sway in the wind. A multi-linked Hookean mechanical structure would move just as you would expect a machine to move, with robotic jerkiness, due to the very nature of Hookean elastic materials. Hookean material has very abrupt transition from stress to unstressed and lends to jerky movements, hence the need for dampening springs with shock absorbers on automobiles. Tensegrity structures restore their full elastic energy more slowly, for example, bent grass returning to its normal, upright stance. Tensegrity structures move as a unit. Tighten one tension member and a ripple of movement runs through the entire structure, be it one cell or billions. The highly integrated flowing movement of the simplest and smallest to the most complex and largest organism is not possible with Hookean systems. Whales and walruses leave no wake, ships and submarines do. The free flowing integrated movement of a bee buzzing; a bat on wing, a baboon swinging, a ballet dancer en pointe, and a basketball player doing a lay-up cannot be matched by any mechanical device. Flemons (**Flemons, 2000**) and others have modeled sculptures from tensegrity units that demonstrate how these structures move in a flowing transition from one configuration to the next.

Elastic structures when deformed store energy and as they return to their original shape, the energy is released. Much of the movement is with stored elastic energy. Stress, and resultant strain, stores energy within the system. In bone and tendons, this energy can be quite large and when modeled as tensegrity structures even more impressive because of its non-linearity and the resulting initial explosive force that automatically smoothes out as it reaches its resting state. Once an icosahedron reaches its resting point, which, unlike Hookean material, is pre-stressed, it will the resist the over reach recoil, non-linearly. This would make for smooth, flowing movements like a pendulum swinging back and forth. Because of its collagen matrix, live bone has the springiness of a vaulter's pole and when the icosahedrons are compressed and released, they would put bounce in each step but not skip him along.

The linkages of icosahedrons are similar to organic chemical linkages. There can be one, two, or three bonds between linked icosahedrons and this imparts varying stability between the links. The joints would be very rigid with three bond linkage and less so with fewer links. A tree most likely has triple bonding. The double tie bar hinge arrangement in the knee is an example of a typical two bar link with the crossed cruciate ligaments under tension imparting rotations and translations with the stored energy of the ligaments assisting in knee flexion and extension. If the spine were linked in such a system movement would cascade up and down the structure like a toy Jacob's ladder. [Fig. 24]

a
b
Fig. 29. A The double cross-bar link model for the knee, B. Jacob's ladder demonstrating a double cross-bar linkage.

Conclusion

It is an engineer's job to understand, simplify and offer predictability when dealing with structures. Imprecise natural processes can only be subjected to approximate descriptions. As Toffler says, "While some parts of the universe may operate like machines, these are closed systems, and closed systems, at best, form only a small part of the physical universe. Most phenomena of interest to us are, in fact, open systems, exchanging energy or mater (and, one might add, information) with their environment. Surely biologic and social systems are open, which means that the attempt to understand them in mechanistic terms is doomed to failure" (Toffler, 1989). Biologic structures are chaotic non-linear, complex and unpredictable by their very nature. The new sciences of chaos (Prigogine and Stengers, 1984; Gleick, 1988) and complexity (Waldrop, 1992)that are needed to explain and understand biologic structural mechanics.

Tensegrity structures have unique characteristics that parallel the structural requirements of biology. The giant leap from Newtonian to tensegrity models in biologic modeling can be taken in small hops. Cells are tensegrity structures. Ingber, in a series of experiments, has proven that the cytoskeleton is a tensegrity structure and it is connected to the nucleus hub, which is also a tensegrity structure. Pulling on the cell wall, distorting its skin, has a direct effect on the nucleus and shows that they are structurally connected through the cytoskeleton. Cletherins, a sub cellular structure is a geodesic dome and geodesic domes are tensegrity structures. Actin, the contractile element of muscle and leukocytes are arranged as geodesic domes. Viruses are icosahedrons, which are the lowest frequency geodesic dome. Radiolaria, volvox, insect eyes, pith, dandelion puffballs and blowfish are all geodesic domes. Carbon60, a basic building bloc of proteins is a self-generating geodesic dome (Kroto, 1988). Unlike Hookean structures, the mechanics of geodesic domes are non-linear. As the structure is compressed, it uniformly shrinks increasing its internal pressure non-linearly. The heart, alveoli, bladder, arteries and all other hollow vesicles within the body do the same. Bone, discs, muscles and ligaments individually and as composites, behave non-linearly. The mechanics and physiology of biologic tissue behave the same way as tensegrity structures.

As already noted, from the physicalist and biomechanics viewpoint, as well as Darwinian theory, the evolution of structure is an optimization problem. At each step of development, the evolving structure optimizes so that it exists with the least amount of energy expenditure. At the cellular level the internal structure of the cells, the microtubules, together with the cell wall, must resist the crushing forces of the surrounding milieu and the exploding forces of its internal metabolism. Following Wolff's law the internal skeleton of the cell aligns itself in the most efficient way to resist those forces. A hierarchical construction of an organism would use the same mechanical laws that build the most basic biologic structure and use it to generate the more complex organism. Not only is the beehive an icosahedron but also is the bee's eye.

Of the known tensegrity structures the tension icosahedron has particular attributes that make it the most suitable for biologic musculoskeletal modeling (Levin, 1986). Icosahedral tensegrity structures are self-organizing space frames that are hierarchical and evolutionary (Figs. 10-14). They will build themselves, conforming to the laws of triangulation, close packing, and, in biologic constructs, Wolff's law and Darwinian evolutionary concepts. In the model we have used, the scapula, fixed in space by the tension of its muscles, ligaments and fascial envelope, functions as the connecting link between the spine and the upper arm, evolved ontogenetically directed not only by phylogenetic forces but also by the physical forces of embryologic development. Wolff and Thompson state that the structure of the body is essentially a blueprint of the forces applied to these structures. Carter theorizes that the mechanical forces in utero are the determinants of embryologic structure that, in turn, evolve to fetal and then newborn structure. What is obvious in the shoulder joint is equally efficient and functional in all other joints of the body, from the cellular level on up. In makes no evolutionary sense to create different mechanical models for each species, from viruses on up, each cell, each tissue, each joint, each position in space, each activity from swimming in the water to walking on land, swinging from trees or flying in the air, when their is one mechanical model that does it all, efficiently and with the least energy expenditure. The biotensegrity model does all this and in any direction and under any conditions.

References:

1. Carter, D. R. 1991. Musculoskeletal otogeny, phylogeny, and functional adaptation. Journal of Biomechanics 24: 3-16.,
2. Flemons, T. 2000. Models, Personal communication.
3. Fuller, R. B. 1975. Synergetics. McMillian, New York.
4. Gleick, J. 1988. Chaos. Penguin Books, New York.
5. **Gordon, J. E. 1978. Structures: or Why things dont fall down**. De Capa Press, New York. Highly recommended as a mechanics primer!
6. ______. 1988. The Science of Structures And Materials. W.H. Freeman, New York.
7. Gould, S. J. 1989. Gratuitous Battle, Civilization, 87.

8. Gracovetsky, S. 1988. The Spinal Engine. Springer-Verlag, New York.

9. Grant, J. C. B. 195? A Method of Anatomy. Williams and Wilkins, Baltimore.

10. Hargittai, I. 1992. Fivefold Symmetry. World Scientific, Singapore.

11. Hargittai, I., AND M. Hargittai. 1994. Symetry: A Unifying Concept. Shelter Publications, Bolinas.

12. Ingber, D. 1998. The Architecture of Life, Scientific American.

13. Ingber, D. E. 1997. Tensegrity: the architectural basis of cellular mechanotransduction. Annu Rev Physiol 59: 575-599.

14. ______. 2000. The origin of cellular life. Bioessays 22: 1160-1170.

15. Ingber, D. E., AND J. Jamieson. 1985. Cells as tensegrity structures. Architectural regulation of histodiferentiation by phsical forces trasduced over basement membrane. Achademic Press, New York.

16. Kroto, H. 1988. Space,stars,C60,and soot. Science 242.

17. Levin, S. M. 1982. Continuous tension, discontinuous compression, a model for biomechanical support of the body. Bulletin of Structural Integration, Rolf Institute, Bolder: 31-33.

18. ______. 1986. The icosahedron as the three-dimensional finite element in biomechanical support. Proceedings of the Society of General Systems Research Symposium on Mental Images, Values and Reality. International Conference on Mental Images, Values, & Reality, 30th annual Meeting SGSR, Philadelphia, U of P, I: G14-26.

19. ______. 1995. The Importance of soft tissues for sructural support of the body. Hanley & Belfus.

20. ______. 1997. Putting the shoulder to the wheel: a new biomechanical model for the shoulder girdle. Biomed Sci Instrum 33: 412-417.

21. Mandelbrot, B. B. 1983. The Fractile Geometry of Nature. Wm.Freeman, New York.

22. Pearce, P. 1978. Structure in Nature as a Strategy for Design. MIT Press, Cambridge.

23. Prigogine, I., AND I. Stengers. 1984. Order Out of Chaos: Man's new diologue with nature. Bantam Books, London.

24. Schultz, A. B. 1983. Biomechanics of the spine. Low back pain and industrial and social disablemen: 20-25.

25. Snelson, K. 2002. Kenneth Snelson@**http://www.kennethsnelson.net/**.

26. Stamenovic, D., J. J. Fredberg, N. Wang, J. P. Butler, AND D. E. Ingber. 1996. A microstructural approach to cytoskeletal mechanics based on tensegrity. J Theor Biol 181: 125-136.

27. Stevens, P. S. 1974. Patterns in Nature. Little-Brown, Boston.

28. Toffler, A. 1989. Science and Change. In I. Prigogine and I. Stengers [eds.], Order Out of Chaos: Man's new diologue with nature, xi-xxxi. Bantam Books, London.

29. Waldrop, M. M. 1992. Complexity. Peguin Books, London.

30. Wang, N., J. P. Butler, AND D. E. Ingber. 1993. Mechanotransduction across the cell surface and through the cytoskeleton. Science 260: 1124-1127.

31. Wang, N., K. Naruse, D. Stamenovic, J. J. Fredberg, S. M. Mijailovich, I. M. Tolic-Norrelykke, T. Polte, R. Mannix, AND D. E. Ingber. 2001.

32. Mechanical behavior in living cells consistent with the tensegrity model. Proc Natl Acad Sci U S A 98: 7765-7770.

33. Wildy, P., AND R. W. Home. 1963. Structure of animal virus particles. . Progresive Medical Virology 5: 1-42.

34. Wolff, J. 1892. Das Gesetz der Transformation der Knocchen. Hirschwald, Berlin.

December 2009