The Tensegrity-Truss as a Model for Spine Mechanics: Biotensegrity

Keywords: Spine, models, biomechanics, tensegrity, biotensegrity.

Abstract: *The commonly accepted 'tower of blocks' model for vertebrate spine mechanics is only useful when modeling a perfectly balanced, upright, immobile spine. Using that model, in any other position than perfectly upright, the forces generated will tear muscle, crush bone and exhaust energy. A new model of the spine uses a tensegrity-truss system that will model the spine right side up, upside-down or in any position, static or dynamic. In a tensegrity-truss model, the loads distribute through the system only in tension or compression. As in all truss systems, there are no levers and no moments at the joints. The model behaves non-linearly and is energy efficient. Unlike a tower of blocks, it is independent of gravity and functions equally well on land, at sea, in the air or in space and models the spines of fish and fowl, bird and beast.*

INTRODUCTION

If the present paradigms of Newtonian based biomechanics hold true, then the calculated forces needed for a grandfather to lift his three year old grandchild would crush his spine, catching a fish at the end of a fly rod will tear the angler limb from limb, and the little sesamoid bones in our feet will crush with each step. The truth is that grandfathers hoist their grandchildren and often toss them in the air, anglers catch 10+ newton weight fish that may dangle from the end of a three-meter long fly rod and the 1000N footballer runs down the field without crushing his miniscule and soft sesamoid bones. The calculations are correct; the paradigm is faulty and ignores the realities of biologic functions. Biologic structures are low energy consuming, open systems, constructed with soft, viscoelastic materials that behave nonlinearly. Calculating loads with the body as a lever-beam, linear Newtonian model will create forces that rip muscle, crush bone and exhaust energy.

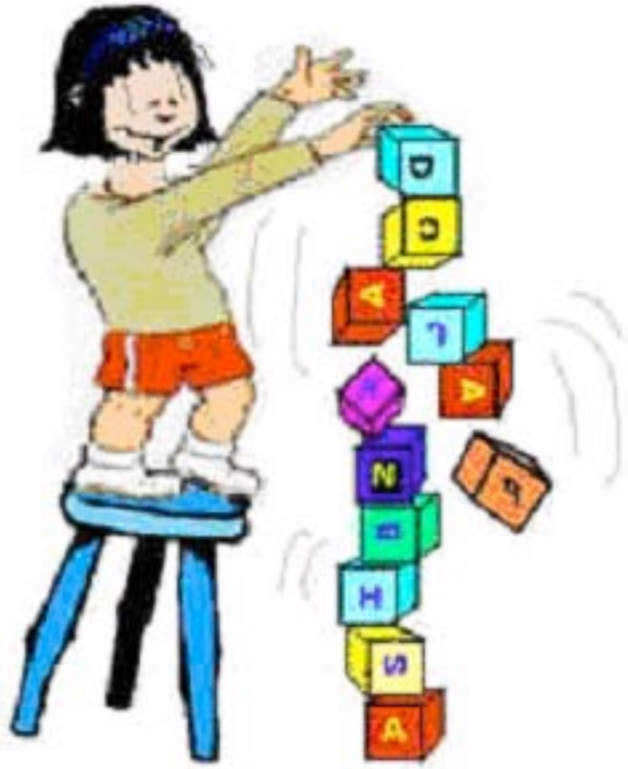

Fig. 1. A Tower of blocks is unstable.

According to conventional wisdom and present paradigms, the human spine and skeleton behaves like an architectural column, a tower of blocks, and supports the body weight as a pillar supports a building.[1] However, architectural columns orient vertically and function only in a gravity field (Figure 1). Columns, pillars, and skyscrapers, are rigid, immobile, unidirectional and base-heavy to withstand crushing forces. They resist compression well but need reinforcement when stressed by bending moments and shear. Stressed by internal shear, they are high-energy consuming structures. Rigid Newtonian mechanical laws such as Hooke's Law, Euler's formula, Galileo's square-cube law and Poisson's ratio govern conventional columns. If biologic systems conformed to these laws, the human bony spine would bend with less than the weight of the head on top of it [2] and limbs will tear off with the leverage of a fly rod held in a hand. Animals larger than a lion would continually break their bones. Dinosaurs and mastodons larger than a present day elephant would have crushed under their own weight. Pterodactyls could never have flown. If governed by simple Newtonian mechanics, urinary bladders will burst when full, pregnant uteruses will rupture with strong contractions, and, with each heartbeat, arteries will lengthen enough to crowd the brain out of the skull.[3] It's not that Newtonian mechanics is wrong; it is that the set of assumptions is wrong. A similar problem arises in geometry. Euclidean geometry tells us that parallel lines never meet. However, on the surface of the earth, lines of longitude are parallel, yet they meet at the North and South Poles. Euclidean geometry is not wrong; it is just that we make a different set of assumptions in order to describe the geometry of the earth. It turns out that Euclidean geometry is a special case geometry where the curvature of the plane is zero degrees. Spherical geometry is non-Euclidean geometry. It appears that bioarchitecture requires non-Newtonian and non-Hookean mechanical thinking that are more adaptable to life forms than are Newtonian and Hookian models.

PRESENT SPINE MODELS

It is a teleological conceit that the human spine acts as a column. From gestation to age one, it never acts as a column. The human spine evolved from quadruped and lesser spines. Phylogenetic and ontogenetic development of the human spine was not in the form of a column, but as some form of a beam. It cannot be an ordinary beam, a rigid bar, but an extraordinary beam that is composed of semi-rigid body segments connected by flexible connective tissue elements that float the segments in space.[4] In many postures, the adult human spine does not function as a column or even a simple beam. When the spine is horizontal, the sacrum is not a base of a column but the connecting element that ties the beam to the pelvic ring.

Even when upright, the vertebral blocks are not fixed by the weight of the load above, as they must be in an architectural pillar. The hallmark of a pillar is stability but the hallmark of a spine is flexibility and movement. Biologic structures are mobile, flexible hinged, low energy consuming, omni-directional structures that can function in a gravity free environment. The mechanical properties are non-Newtonian, non-Hookian and nonlinear. Columns need a stable base on which to rest. Therefore, columns are not useful as a model for fish or fowl or man in space. A post and beam is inadequate to model the neck of a flamingo, the tail of a monkey, the wing of a bat or the spine of a snake. Joints are slippery slopes and shear cannot exist in a frictionless joint. All forces must be normal to the surface to transmit loads. Post and beam modeling in biologic structures could only apply in a perfectly balanced, rigid hinged, immobile, upright spine with all joint surfaces normal to the force of gravity.

The spine can bend forward so a person can touch toes and bend backward almost equally well. It can twist and bend simultaneously. It can perform intricately controlled movements in space as done in gymnastics, dance, aquatic diving or basketball. With each breath, the interconnected vertebrae translate, some forward, some backward. While architectural columns bear loads from above the human spine can accept loads from any direction with arms and legs cantilevered out in any way. The hallmark of a pillar is stability but the hallmark of a spine is flexibility and movement. Movement of an articulated column, even along a horizontal, is more challenging than moving an upright Titan missile to its launch pad. 'S' shaped curves can create intolerable loads and instability in a column, particularly if it is a thin, articulated column that has flexible, frictionless joints, as the spine does. The spine is flexible, mobile, and functionally independent of gravity and has property behavior inconsistent with an architectural column or beam.

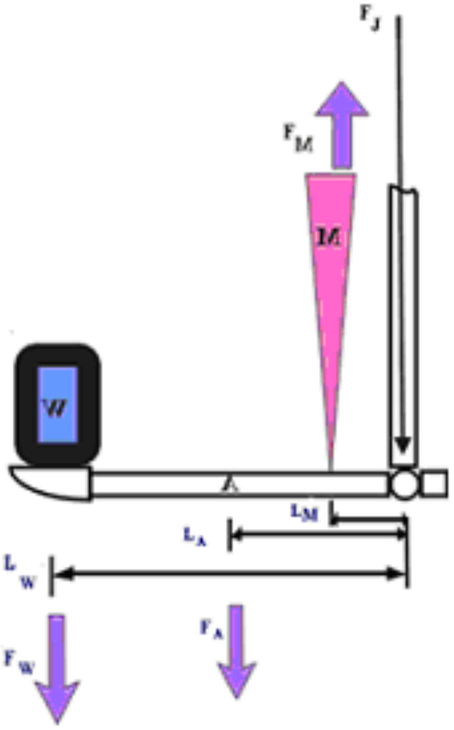

Fig. 2. The arm as a lever.

The free body diagram has been the reductionist approach to biomechanical modeling. Each segment is modeled in isolation. As noted by Ait-Haddou[5] and others,[6, 7] joints are spanned by tension elements that may span two or more segments. For example, the usual model for the elbow joint is the 90°-flexed elbow that supports a weight in its hand balanced by the biceps brachii muscle with the formula:
$F_A \times L_A + F_W \times L_W - F_M \times L_M = 0$.
F_M

is the weight of the load in the hand and F_A is the weight of the arm[8] (Figure 2). However, the free body diagram poorly represents the true forces that must act in concert about any joint in the body. In the arm, the biceps is a two joint muscle and crosses the glenohumeral joint in addition to the elbow joint. As the biceps crosses the glenohumeral joint, that creates a moment at the shoulder. The glenohumeral joint is stabilized be antagonist muscles, such as the triceps, which is a muscle that extends the elbow and it must then enter into a feedback loop with the biceps. Holding a weight in the hand requires the use of the wrist flexors and finger flexors. They also cross the elbow joint and will create moments that need to be counterbalanced with the triceps, and so on. The glenohumeral joint connects to the axial skeleton through the scapula, which suspends from the chest wall by muscles that must also enter into the feedback loop. It is clear that there are no sharply defined segment boundaries. In the scapulo-thoracic complex, no rigid structure that can act as a fulcrum as there is no bone-on-bone contact. Without a fulcrum, there is no lever. Any moments passed from arm to axial skeleton is only accomplished through the tension of muscles. You can only pull with a muscle, it cannot act as a rigid lever.

Loads calculated when using free body analysis frequently exceed known tissue capabilities. In the usual free body analysis of the hip, the calculated loads are seven to ten times body weight. With a 1000 N footballer running down the field the calculated load on the articular cartilage will be in the range of 12-15 MPa and more. It is a poorly kept secret that articular cartilage is incapable of sustaining the calculated loads on it without considerable help.[9] The erectores spinae muscles can only withstand loads of 2000-4000N. During weight lifting, using free body analysis, the loads on the erectores spinae can exceed 16000N.[10] Clearly, free body analysis misrepresents the true picture. Free body diagrams are inadequate and even deceiving, approximations of the true forces at any one joint.

ALTERNATIVE MODELS

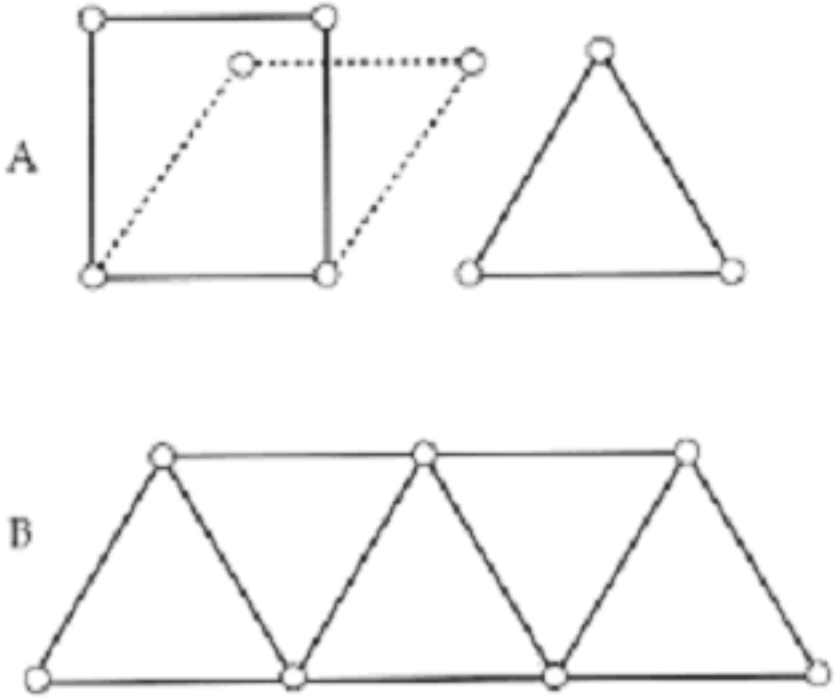

Fig. 3. A. Square frames are unstable and create torque at the joints. Triangular frames are inherently stable. B. A simple, planar truss.

There are alternative models to the column that may be more appropriate for spinal models of all species, not just bipeds. D'Arcy Thompson[11] and, latter, Gordon[12], use truss models. A truss is fully triangulated and is inherently stable and independent of gravity. Trusses have flexible, even frictionless, hinges with zero moments about the joint. Loads applied at any point distribute about the truss, as tension or compression. There are no levers within a truss. Only trusses are inherently stable with freely moving hinges. Vertebrates are stable, with flexible joints and, therefore, constructed as trusses if they are to stand upright. Thompson compared a dinosaur to a trestle bridge with the bones as the compression elements and the muscles and ligaments as the tension members. In a truss, the loads distribute through the system, as tension and compression only and the joints can be pin hinges, as there are no moments generated (Figure 3).

In two dimensions, we can start with a single triangle, the basic truss, and add more triangles. Three dimensional, or space trusses, are some combination or permutation of the three regular polyhedrons that are fully triangulated, the tetrahedron with four triangulated faces, the octahedron with eight and icosahedron with twenty (Figure 4). The icosahedron has some distinct advantages in biologic modeling. It has the largest volume for surface area, an economy of resources, and has the ability to be close packed to fill space.

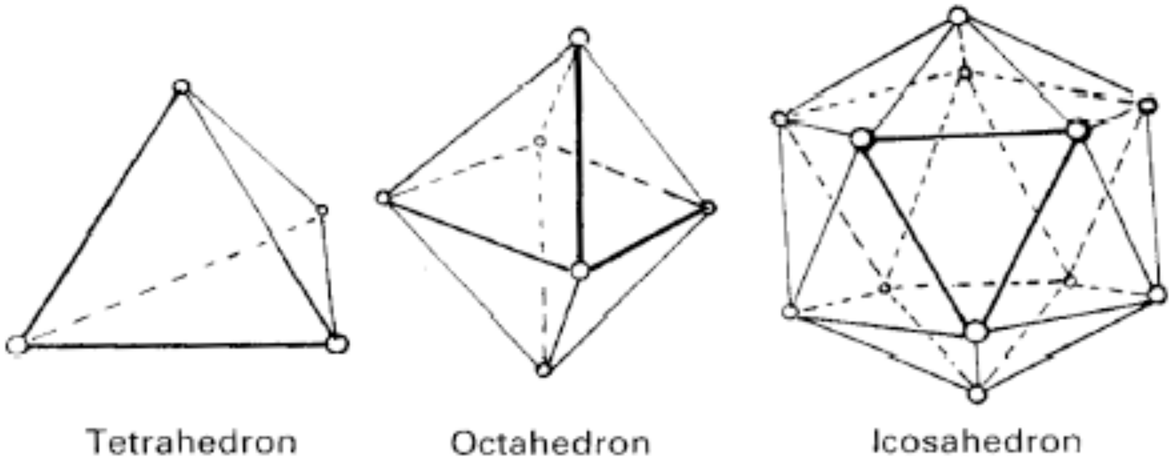

Fig. 4. Three dimensional, fully triangulated, regular polygon trusses. Only fully triangulated polygons are stable when the joints are flexible.

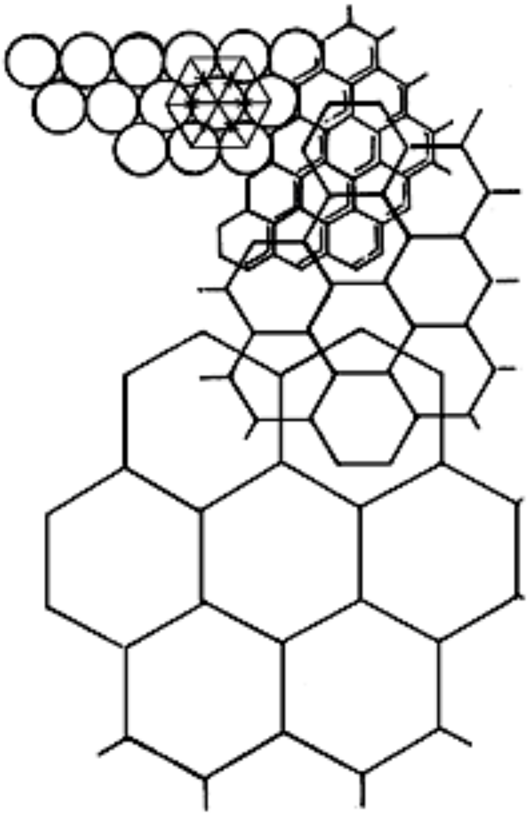

Fig. 5. Hexagonal close-packing. Self-generating tessellation of a plane.

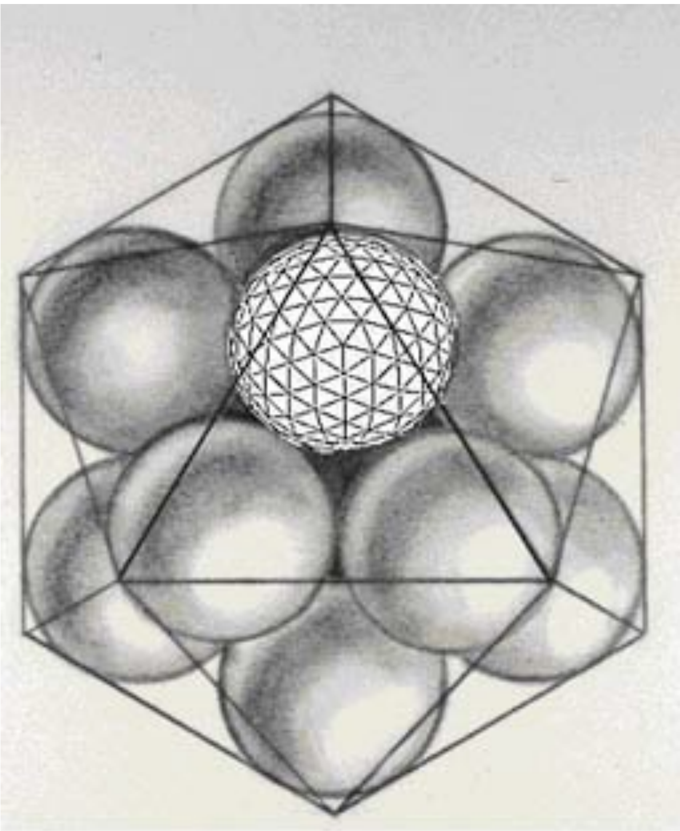

Fig. 6. Close packing of icosahedral geodesics about a central space. Self-generating tessellation in three-dimensional space.

The inter-related concepts of triangulation, close packing, space filling and least energy consumption are fundamental to structural evolution.[11, 13] In two dimensions, space filling is a hierarchical close packing of hexagons with their centers connected by triangles (Figure 5). The polyhedral structure that is the core of three dimensional close packing is less apparent, but what is known for certain is that the faces of the adjacent polyhedral cells always meet in threes with an dihedral angle of 120° and four edges meet at a corner with angles of 109°. Twelve pentagons, which have five fold symmetry, will not close pack a zero degree plane as only three-fold, four-fold and six-fold symmetry will tessellate a zero degree plane. Tessellating five-fold symmetry pentagons, they will fold in on itself and generate a closed space dodecahedron with twelve pentagonal faces, twenty vertices and thirty edges. Dodecahedrons, with five-fold symmetry, are not triangulated and, therefore, unstable three-dimensional structures. If the center points of the faces are connected, we create the dual of the dodecahedron, the fully triangulated and stable icosahedron with twelve vertices, twenty triangular faces and thirty edges. Icosahedrons also demonstrate five-fold symmetry. The icosahedron can exist independently as a structure and, with its sides meeting at 119o and edges meeting at 108°, comes close to the ideal. Fuller[14] showed that twelve icosahedrons could close pack around a central nucleus and will tessellate into a larger icosahedron and leave a small icosahedral shaped vacuole in the middle (Figure 6). This is the most symmetrical distribution of spheres packed around a central point. Mathematical close packing requires equal size polyhedrons. Mother Nature does not require perfect symmetry and slightly unequal size icosahedrons close pack very well. Although the concept of 'fractals' [15] was not known at the time Fuller was writing about icosahedrons, he did draw that phenomenon, albeit, unknowingly. It is easy to see by looking at his drawings how foams[13] support each other by sharing structural elements that fit the close packing mathematical requirements. The space filling is hierarchical and the structure is a fractal generator so that self-similar structures evolve as more icosahedrons link with one another, simplicity evolves into complexity. Viruses, clathrins, cells, Volvox, radiolaria, bee's eyes and pollen grains, are icosahedrons. The Icosahedron is the basis for Buckminster Fuller's geodesic domes[14], which are high frequency icosahedrons. A geodesic dome is a "tensegrity" structure, defined by Fuller as 'continuous tension, discontinuous compression', and, as such, has some unique mechanical properties, but first, let us clarify 'tensegrity'.

TENSEGRITY

One of the more familiar tensegrity structures is the wire spoke bicycle wheel. A wagon wheel vaults from spoke to spoke, bearing full load on each spoke in turn. It needs thick spokes and a thick rim to support compressive loads. The wire wheel has a compression-loaded hub, which is separated by multiple tension-loaded spokes from its compression-loaded rim. The spokes are under constant, equal tension. We now have continuous tension of the spokes separating the discontinuous compression elements, the hub and rim. As we have noted, Buckminster Fuller's geodesic domes with a hollow, almost spherical structure, are also tensegrity structures. Geodesic domes are high frequency icosahedrons with the faces of the icosahedron subdivided in regular multiples conforming to the formula, $F + V - 2 = E$, where F = the number of faces, V = the number of vertices and E = the number of edges. If we tessellate icosahedrons they close pack into structurally stable icosahedral shells in the relation of $10(m-1)^2 + 2$, where m is the number of smaller icosahedrons along each edge of a higher order icosahedron, the numbers being twelve, twenty-two, ninety-two and so on.

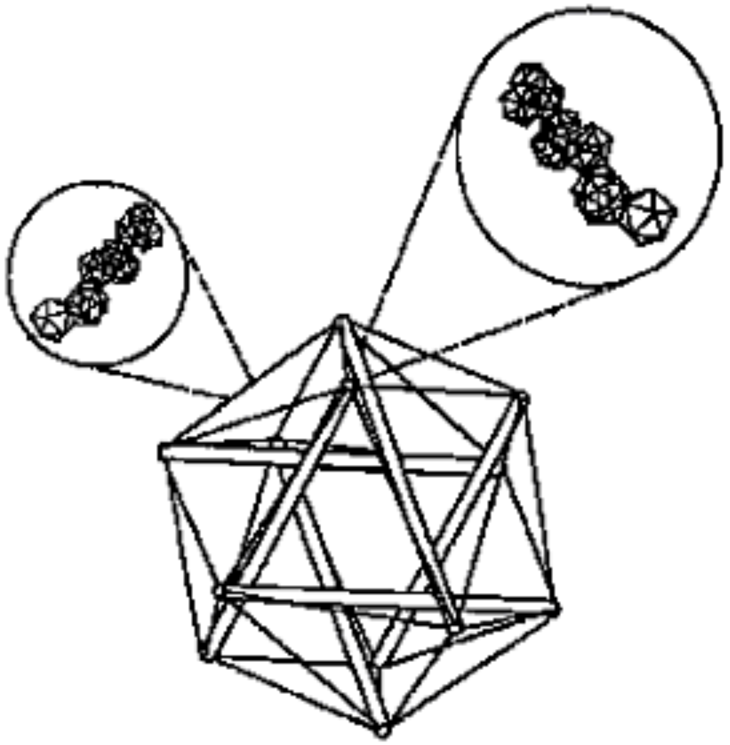

Fig. 7. Tensegrity icosahedron. A hierarchical construct with each element a chain or column of stacked icosahedrons.

In geodesic domes, many of the rigid-looking parts of the external frame are really tension elements. In the most basic geodesic dome, the icosahedron, pressure on any point transmits around the edges with some of the edges under compression and some under tension. Any truss does the same. In an icosahedron, five edges come together at a vertex; hence, the five-fold symmetry. It is possible to transfer the entire compression load away from the outside of the structure. When we connect the opposite vertices with one of six new compression members which transverse the interstice of the icosahedron, they push the vertices from the center. The internalized compression members do not pass through the center of the icosahedron but are eccentric and slip tangentially past each other without touching. The outer shell is then a tension membrane with compression rods as an inner frame (Figure 7). The entire structure is a rigid, sphere-like geodesic, a tensegrity icosahedron, with a skin under tension and the endoskeletal compression elements enmeshed in the interstices but not compressing one another. This functions just like the wire bicycle wheel, but inside out. Increasing the frequency and the number of vertices that are kept apart increase the number of internalized compression members but they still do not compress one another. Ingber[16] uses this structure to model the cell.

Some of the unusual mechanical properties of icosahedral trusses, particularly the internally vectored endoskeletal icosahedrons, are that they have a nonlinear stress-strain curve which is considered by Gordon[12] to be the essential element of biologic materials. They exhibit creep and visco-elasticity, and they can be self-assembling and structurally integrate. The load on one icosahedron is distributed and shared by other structurally integrated icosahedrons, just like the sharing of tension loads in a wire wheel. The structures do not have to be round but can stack in a column or helix and take on any shape, with the whole structure mechanically functioning as one. In a hierarchical construct, the compression bearing columns can be stacked icosahedral truss towers that structurally link. When an icosahedron is loaded in tension or compression, it does not bulge or thin out in the middle. Instead, the whole structure contracts or expands and becomes denser and stronger or less dense and weaker, non-linearly. If it were a fluid-filled pump, it would push the fluid out more forcefully as it emptied because the internal pressure rises as the icosahedron compresses. The non-linearity also occurs when the load is released and allows for a soft landing, shock absorber effect.

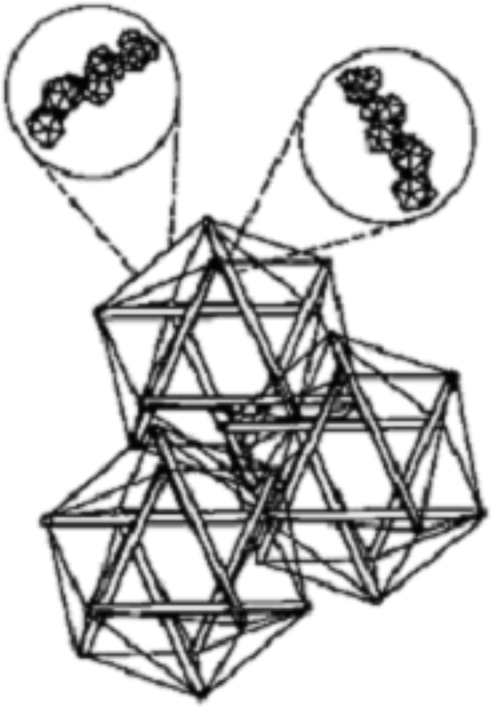

Fig. 8. Fractal, hierarchical,construct of tensegrity icosahedrons.

Tensegrity trusses are tension structures with only short, isolated, compression elements. Euler's slenderness ratios are not applicable and the structure can be as long, high and as thick as necessary. The shell of geodesics is under tension, and they are trying to expand rather than collapse into itself. They explode rather than implode. Instead of crushing of its own weight, the larger and more sub-divided, the stronger it becomes. A giant geodesic dome is structurally stronger than a mini-dome.[14] Just as a muscle increases in strength as its cross sectional area increases, so does bone, not under the compression of its weight but under the tension of its collagen matrix. All this allows for brontosaurus-size bones that become stronger as they increase in size while they remain the same density. Dinosaurs necks can be ten meters long, flexible hinged, fully integrated tensegrity trusses that can function vertically or horizontally right side up or upside down and Pterosaurs' wings would not tear apart. In two-dimensional close packing, hierarchical hexagonal patterns are generated, as they are the most energy efficient means of space filling. In three dimensions, twelve spheres or geodesics close pack about a central, icosahedral shaped space. This mirrors viral self-assembly of twelve spherical or geodesic proteins that pack around a central space and this gives us the icosahedral shape of viruses. Hierarchical close packing of geodesics can continue, ad infinitum, building larger and more complex structures (Figure 8). This geodesic pattern is presently recognized in viruses, clathrins, single cell structure, volvox, radiolaria, pollen grains and dandelions. It is also seen in fat cells, liver parenchyma and the alveoli of lungs. Whole organisms, organelles and various tissues are shown to be[17], or behave as, tensegrity icosahedrons. With tensegrity, giant dinosaurs are self-assembled in the same way as viruses.

All this occurs independent of the material and relies only on the structure. It can be rigid or less so, depending in the materials and the changing tension in the system. Increasing the "tone" of the tension elements may increase the rigidity of the structure. Shortening or lengthening a tension edge alters the shape of one of the triangles in the icosahedral truss and the whole structure may change shape and/or move.

Let us assume human, whole body modeling, as tensegrity structures. Changing muscle tone would alter the body posture, from recumbent to standing. Once the tone is set, no further muscle activity is necessary to maintain that posture, as the truss is stable. For instance, during quiet standing, no additional muscle contraction would be necessary and the EMG would not record any significant activity. Muscles act in unison, rather than antagonists, as they are the tension elements of the truss. Loads applied at a point, say, the sesamoid bones under the first metatarsal, distribute their load through the tension system and compression system of the body, just as the point of contact of a wire wheel distributes its load through the spokes and rim. There is instant communication amongst all the cells by force transduction. The small bones of the hands and feet are part of the total system and function as truss members. The compression loads on joints transmit through tension in the soft tissues. Only tension and compression exist in the system and there is neither shear nor are there moments. As loads are applied to the system, the strength increases. Muscles become stronger as they contract. Bones become denser and stronger as loads are applied. The hollow organs are tensegrity pumps. As they contract, the internal pressure increases. In the heart, the blood pressure goes up with systole. As air from the lungs expels, the alveolar pressure increases. Bladder and bowel pressure increase with emptying and the hollow organs can expel the last drop. This is the human body, as we know it.

MODELING THE SPINE

The human spine was not designed to be an upright column, it just evolved that way. It evolved following the pattern laid out for it by its genes and the rules of physics. To quote D'Arcy Thompson, "Cell and tissue, shell and bone, leaf and flower, are so many portions of matter, and it is in obedience to the laws of physics that their particles have been moved, molded and conformed." Nature took the material available and, bit-by-bit, that material evolved into its various life forms. Once a single cell evolved, physical laws dictated how they would structurally relate to one another. Crowded together, they will close pack and follow the rules we have already discussed. They adhere to one another by the rules surface tension and, once interlukins[18] evolved, by the attachment of their interlukins to each other. Interlukins are attached to the tensegrity microtubular structure of the cell. It is energy efficient for cells to specialize and cells evolve into tissues. The mechanical support system of biologic organisms follows that pattern. The "skeleton" of a cell is its microtubules, which is a tensegrity stucture, and its "muscle" actin, forms a tensegrity network.[18] Stiffeners become deposited, silica in sponges, chitin in some creatures, chondroitin in others, hydroxiapetite in bone formers, but they are small crystals, compression elements, that are enmeshed in a soft, collagen network. Bone is more a starched, stiff shirt than a suit of armor. The skeleton network will obey the same physical laws as all other matter. The genes that blueprint the evolving structure evolve themselves and the most energy efficient structures take hold. Nature's principle of "minimum inventory, maximum diversity"[17] dictates the recycling of structural forms. The spine that evolved to be the compression resisting elements and motor in the fish[10], evolve to be the compression resisting elements and motor on land. The same elements that go into constructing the spine of a baboon, at the micro and macro level, are used in constructing the spine of a biped human. All that need be done is to tuck in the tail and form a lumbar lordosis. If the same principle that is used in evolving cell, tissue and organism is used in the evolving spine then it, too, will be a tensegrity structure.

A model for this is Snelson's "Needle Tower" (Figure 9). In it, the compression elements are enmeshed in a fractal construction of tensegrity icosahedrons. Compression elements "float" in the interstices of tension wires. It is rigid, strong, lightweight and omni-directional. The tower functions as a column but does not depend on gravity to hold it together. It works equally well as a beam and all the same elements that are under tension or compression remain under pure tension or compression with no joint moments, no mater what its orientation. Flemons (Figure 10) has constructed a model that more closely resembles a spine and uses the same construction principles as Snelson's tower. Tightening one of the tension elements changes the shape of the whole structure. All elements instantly respond by changing position and a new and stable posture is immediately assumed.

Fig. 9. "Needle Tower", Kenneth Snelson, Hirshhorn Museum, Washington, D. C.

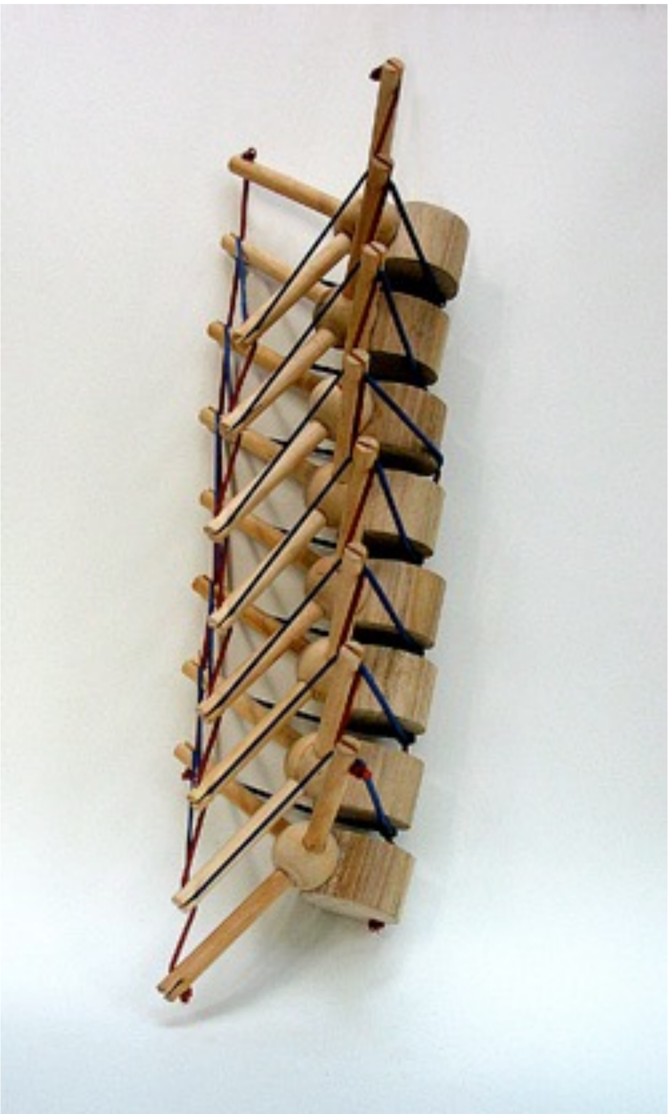
Fig. 10. Tensegrity spine.

CONCLUSION

Others have challenged the perceived inadequacies of the current total human body models and several issues are raised.[19,20] Biotensegrity, the application of Fuller's tensegrity concepts to biologic structure and physiology, apparently can be used to successfully model the spine and other organ systems. In this system of total body modeling, the limbs are not an assemblage of rigid body segments. They are semi-rigid non-linear, viscoelastic bony segments, interconnected by non-linear, viscoelastic connectors, the cartilage, joint capsules and ligaments and with an integrated non-linear, viscoelastic active motor system, the muscles and tendons and connective tissue. The visceral organs integrate structurally and physiologically into the same system. There are no limb segment boundaries and the smaller bones and joints of the hands and feet fully integrate into the mechanical model. The spine is a tensegrity tower that integrates with the limbs, head and tail and to the visceral system, as well. A change of tension anywhere within the system is instantly signaled to everywhere else in the body and there is a total body response by mechanical transduction. The structure works equally well right side up, upside down, in sea, land, air or in space. It resolves many of the inadequacies of present models.

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