# The Geometry of Anatomy – the Bones of Tensegrity

Among clinicians and bodyworkers today, there appears to be a great deal of interest in the concept of tensegrity as it applies to living forms, but much confusion as well. In some circles it seems to be the flavour of the decade but what are they talking about? What exactly is a tensegrity? Is it a useful scientific description and explanation for anatomical function? Or is it just a metaphor for the intuitive feeling that bodies behave as whole systems held in connective tension? If the latter, it's as good or better than any other analogy and the definition can remain vague. But if tensegrity claims to explain the biomechanics of living structure, then more is required. A clear definition of "biotensegrity"and a means to test the hypothesis is needed. The actual relations between tension and compression components in the body need to be examined. Can biotensegrity help explain the complex interplay of these forces in biomechanical terms and if so what does that imply? One mark of a valid scientific hypothesis is its predictiveness. If tensegrity provides better descriptions, does that make for better prescriptions?

I'm not an anatomist, a biomechanist, or a body worker. I've come to this work as a geometer with fresh eyes and new ideas. I make tensegrities for a living and for pleasure – toys, furniture, sculptures, mobiles and biotensegrities, and the focus is always on how something is built. I pay attention to details. In the case of living things, I've tried to apply what I've learned about the geometry of structure to, in effect, reverse engineer evolution. I'm looking for the most material and energy efficient strategy to organize and design self assembled, strong, resilient, repairable, flexible, lightweight mobile frameworks.

Quite a mouthful, but put this way, I can focus on the geometry of the body and speculate on how and if, it is composed of patterns identifiable as tensegrities.

My tensegrity models are abstractions of the body designed to approximately diagram forces and movements that act on anatomical structure. Looking for a close match in form and function, I have attempted to model human form and function using only this principle. Many iterations later I'm still testing the hypothesis.

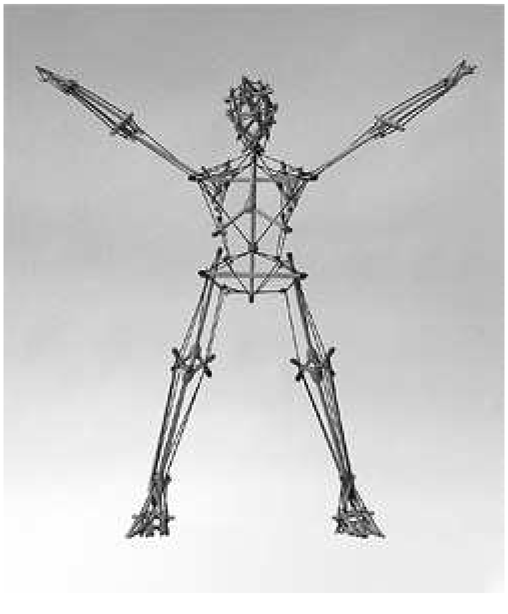

Fig 1. Tensegrity Skeleton

Tensegrity geometry is a language I've used to interpret and represent anatomic form as a dynamic interplay of forces in four dimensions (bodies moving through time). What I've found out is intriguing– movement and degrees of freedom in the models seem roughly analogous to human movement and freedom. In addition, changes to one part of the model (e.g. local increased tension) are reflected throughout the structure; this is similar to the observation that pain in the body often occurs at a distance from the source of insult. This is suggestive but it isn't proof. Beginning to work out the details of the theory is what this paper attempts to address.

## Tensegrity is...

Tensegrities are all about tension and compression. Every structure, whether an artifact created by intelligence or a living form evolved by natural selection, is a balance between these two and only these two forces. Engineer and architect Mario Salvadori points out in his book *Why Buildings Stand Up,* that shear is equivalent to tension and compression forces acting at right angles and is not a separate force.[1] Tensegrities are special case structures where the play of these two forces is visible in the design.

But tensegrity is also certainly one of the most powerful memes in the modern era. I think this is because of the elegance and power tensegrities have to describe and illustrate the behaviour of whole systems as fractals. Tensegrity is a potent metaphor for envisioning existence in syncretic and non–atomistic ways. It has come to be imbued with multiple meanings at many levels of intercourse…

Carlos Castaneda appropriated the term as… "The name given to the modern version of the magical passes: positions and movements of body and breath that were dreamt and stalked by men and women seers who lived in Mexico in ancient times…"2 It turns out that Castaneda admired R. Buckminster Fuller who coined the term; he then borrowed and copyrighted the word for his own purposes.

The Canadian theoretician Stafford Beer, the founder of Management Cybernetics also admired Fuller and used tensegrity as a social metaphor to describe complex decision-making relationships in groups. He coined the term Syntegrity as tensegrity had already been copyrighted…

The Wikipedia weighs in with, "Tensegrity is a portmanteau of tensional integrity. It refers to the integrity of structures as being based in a synergy between balanced tension and compression components."[2] Synergy refers to the observation made first by R. Buckminster Fuller that in any system the whole is always greater than the sum of its parts. The behavior of tensegrities is a visual demonstration of this.

How does Fuller define it? From Synergetics 700.011: "The word tensegrity is an invention: it is 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."[3] Easy for him to say… Fuller went on to design the largest enclosed domes ever built utilizing tensegrity principles.

The sculptor Kenneth Snelson who made the first tensegrity structures in 1948 called them something different. In an interview he said, “Tensegrity, the word, has become so confusing through multiple uses that it calls any definition into question. This is the reason I've long advocated Floating Compression… (It) describes a closed structural system composed of a set of three or more elongate compression struts within a network of tension tendons, the combined parts mutually supportive in such a way that the struts do not touch one another, but press outwardly against nodal points in the tension network to form a firm, triangulated, prestressed, tension and compression unit. Why triangulated? The reason is that it's possible to build such a structure whose network is non-triangulated. Such structures are flaccid and decidedly not firm.”[4] In the art world Snelson is well known and his floating compression sculptures are found in galleries, private collections, and museums around the world.
(http://www.kennethsnelson.net/faqs/faq.html)

A tensegrity requires at minimum three conditions to fit either Kenneth Snelson's or Buckminster Fuller's definition.

1. A continuous connective tensioned network supports discontinuous compression struts. Snelson insists that struts must be free floating in a web of tension and not touching. A geodesic dome, which Fuller considers to be tensegrities, has multiple compression struts meeting at central hubs but they are discontinuously connected, that is, they do not transfer compressive loads. In these domes it is the tension forces that travel along the outer edges of the struts that are continuous. Similarly, if anatomical structures operate as tensegrities, then in most orientations the bones do not pass a direct load across the joint– rather the tension members; ligaments, tendons, and fascia transfer loads and the bones float in this tension matrix.

2) All tensegrities are prestressed under tension; they are self–supporting and independent of gravity. But the weight of the structure also adds to the prestress. As you increase the weight load the tensegrity tightens and gets smaller. The heavier the structure is, the greater the tension, and the less the range of motion. This presents real design problems when trying to model living systems that have and use joints with multiple degrees of freedom. My models for example can emulate biologic movement because I use elastic tension nets that are taut enough to maintain the shape of the model yet have enough residual elasticity to move through a wide range of positions. When the size and weight of a model increases, so does the prestress. It is always surprising to discover how high the tension levels climb when building large tensegrity structures. In some of Snelson’s largest sculptures (50’–100’) the tensile cables carry thousands of pounds of force. To make human scale tensegrity models that articulate and are prestressed is not a trivial challenge.

3) Tensegrities are self–contained non–redundant whole systems. All components are dynamically linked such that forces are translated instantly everywhere; a change in one part is reflected throughout. These features distinguish tensegrities from all other tension structures, e.g. a radio mast or a sailboat’s mast is fixed at the base and needs that fixed point to keep it upright. The boat does not need the mast for it’s integrity but the reverse is

not true. Every part in a tensegrity is reliant on the entire structure for its continued existence. In terms of living forms, a discontinuity in a structure marks the boundary or interface between separate tensegrities. Also, molecules within cells within tissues within organs within bodies, and bodies within environments are all synergistically linked tensegrities in a hierarchical cascade from the smallest wholes to the largest.

At the macro scale of human anatomy, I see tensegrity as a diagrammatic way to model in four dimensions forces acting on complex shapes in terms of stress vectors. I suggest that this analytic technique can explain the structure of individual bones as well as aggregates that make up the body.  Tensegrity in this sense is an applied principle– a map of the nature of structure. If tensegrity is seen not so much a building system as it is a description of the most efficient way that all form is organized, in terms of most economical use of energy and material, then we would expect parsimonious nature to utilize this principle universally. The task is to determine exactly how this might have been achieved at each scale of the continuum.

## Biotensegrity

In the last 25 years tensegrity has come to be associated with various inquiries into the nature of living structure. Donald E. Ingber MD PhD, Professor of Pathology at the Harvard Medical School, has done cellular research that has been widely reported in major scientific journals as well in Scientific American, The Architecture of Life, January 1998. He has found conclusive evidence that tensegrity provides the best explanation for the cytoskeleton of the cell, its movement and behavior. Stephen Levin M.D., an orthopedic surgeon who coined the term biotensegrity has applied the principle to macro scale anatomy in papers and numerous lectures around the world for over 25 years. His vision of biomechanical biotensegrity is radical and comprehensive. (biotensegrity.com). Others such as Tom Myers, well known writer and teacher of Structural Integration (http://www.anatomytrains.us/), and George Roth a writer and chiropractor from Toronto (http://www.matrixinstitute.net/) both use the term in helping explain their practice and methodology but the usage is general and mostly metaphoric. There are many others writing on this subject, but not everyone understands tensegrity in the same way. And some clearly understand less…

In a paper for an osteopathic journal, an American osteopath used tensegrity to model cranial sacral work but labeled a picture of a train trestle bridge an example of tensegrity. The trestle bridge is an open braced framework– a truss that conveys forces to the ground through the compression members– this disqualifies it as a tensegrity. A physiotherapist interested in the concept thought that a spider’s web was a tensegrity structure. But a spider’s web is arranged the same as a trampoline– a flexible tension membrane suspended from an exterior framework which is independent of the membrane. The branch doesn’t rely on the web for support but the web needs the branch. Individual tensegrities are integral– all parts are connected in a non–hierarchical relationship. A body worker who uses tensegrity as a metaphor compares it to a mast in a sailboat. But a ship’s mast acts as a lever arm whose fulcrum is the deck of the boat (which doesn’t rely on the mast for its integrity) and is prevented from tilting by tension shrouds. Tensegrities have no lever arms or fulcrums in the classical sense. Forces are transferred globally across the entire structure. A well–known teacher of yoga teachers, who talks about tensegrity in her instruction, thought she lives in a tensegrity house because it had triangular roof sections. She no doubt has a stable roof but it isn't a tensegrity. Each of these clinicians has used tensegrity as an analogy based upon tension structures or stability through triangulation to describe their work but no one is using the term correctly. All tensegrity structures are tensile but not all tensile structures are tensegrities. As we are bound together with connective tissue that acts in tension, it is legitimate to ask what kind of tensile form we are.

## Geometry of Tensegrity

The yoga teacher was partly right; it is about triangles. The only way to fully stabilize and constrain any structure is by triangulating surfaces or cavities in compression and/or tension in all three dimensions. This fact may not be obvious at first as many artifacts conceal their triangulation within their form such as the square walls and roofs of buildings. Tensegrity structures on the other hand show the forces acting upon them by differentiating out tension and compression vectors into separate components. Most are based upon iterations of regular geometric forms known as the five Platonic Solids. Complete triangulation and full stability occurs in only three of these, the tetrahedron, octahedron and icosahedron and these are the best candidates for modeling anatomy. Without triangular bracing, the cube and the dodecahedron are inherently unstable. All five convex regular polyhedrons demonstrate faces, edges and angles that are congruent, that is, all faces are equilateral, all angles are the same and all the edges are identical.

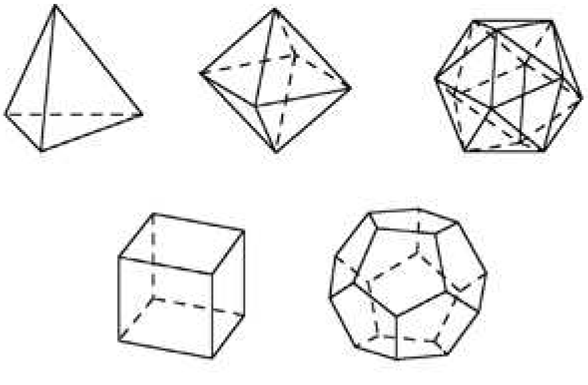

Fig 2. Platonic Solids

But as Fuller pointed out, the Babylonians, Egyptians and Greeks modeled their geometry on the mistaken notion that objects were solid, planes were smooth and bounded by edges, and edges met at a point. Physics discloses no evidence of a continuum; reality looks and behaves more like a tensegrity– aggregates of non–solid events mediated solely by tension and compression vectors of force. Further, no two events pass through the same point– rather the tension and compression vectors twist past each other lending torque or rotation to geometry. Tensegrities always possess clockwise and counterclockwise rotations of compression and tension that additively cancel each other out to guarantee stability.

Tensegrity models of the Platonic Solids can reveal the forces that act on their forms. By studying the geometry of the body it seems likely that appropriate tensegrity forms can similarly be used to model the forces acting upon it and to explain systemic function and dysfunction. Of the three regular triangulated polyhedra only the octahedron could be said to possess symmetry in all three axis. A tensegrity version of this called an expanded octahedron is the appropriate model to use where we find these symmetries in the body.

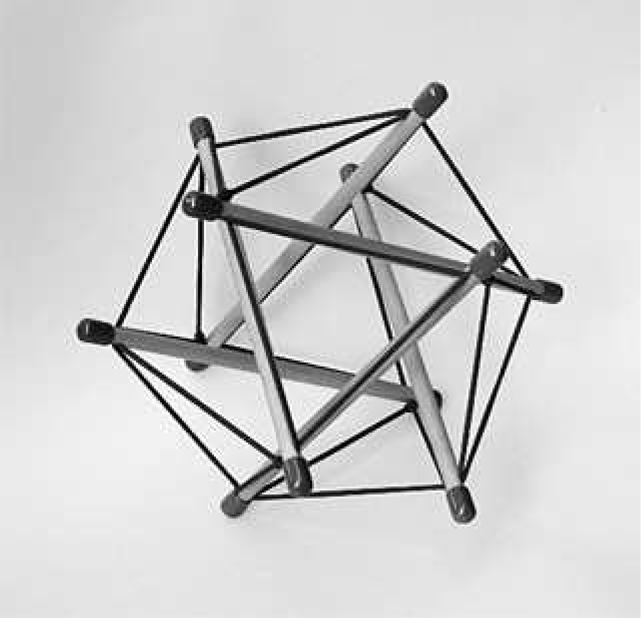

Fig 3. Expanded Octahedron tensegrity

Other classes of tensegrities are chiral, that is they come in left and right–handed versions of what look like skewed or rotated prisms. These seem more appropriate as asymmetrical models of the hands and feet.

In living structure, stability is paired with mobility and objects that are adapted to allow movement possess degrees of freedom and are not fully triangulated. Degrees of freedom refer to the number of different ways in which a rigid object can move in three dimensions (six). They are: movement up and down (heaving), movement left and right (swaying), movement forward and backward (surging), angling up and down (pitching), turning left and right (yawing) and tilting side to side (rolling). A mechanism or linkage connecting more than one object may have more than the degrees of freedom for a single rigid object. The human arm for example is considered to have seven degrees of freedom, three at the shoulder, one at the elbow and three at the wrist. Controlling degrees of freedom means increasing the stability of an object and in any joint all other unwanted degrees of freedom are constrained by a combination of bone geometry and connective attachments.

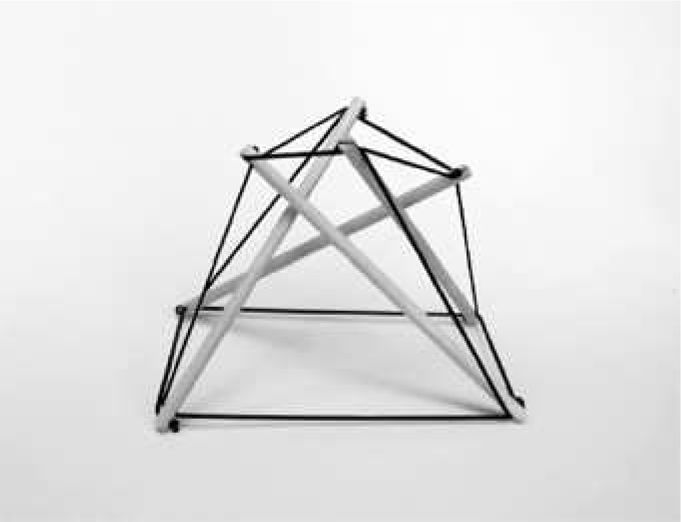

Fig 4. Four-fold Tensegrity Prism

Because tensegrities are never completely rigid, they have varying degrees of freedom whose range of motion is determined by their triangulation. In this respect they are superficially more similar to plants than to mobile beings. They can flex and accommodate to vectors of force by slightly altering shape. They bend rather than break. But the peripheries of the body demonstrate wide ranges of motion that vary in each joint. For tensegrities to emulate anatomy there must be an increase in ranges of motion without sacrificing stability or degrees of freedom.

In medical terminology, range of motion is the measurement of the distance achievable between the flexed position and the extended position of a particular joint or muscle group usually measured in degrees. But there's no talk of articulation in tensegrity's definitions. In fact if you look at Fuller and Snelson's tensegrities, they approximate a sphere, dome or a mast – there are no joints. The larger they are and the more they weigh, the more load stress is added to the prestress and the less range of motion they possess. This is key in attempting to find a fit between anatomy and tensegrity. How does the concept, principle and theory relate to the complex arrangement of irregular shaped bones, and the fascia, ligaments and tendons that act across articulating joints in our bodies?

One attempt to answer this conundrum, models the actual shape of the bones with their attachments as tensegrities. There is a direct relationship between an applied load and the morphology of bone. Wolff's Law of bone transformation says that every change in the function of a bone is followed by certain definite changes in internal architecture and external conformation in accordance with mathematical laws. This means that the external shape of a bone is well adapted to the forces placed upon them. In other words, the geometry of the bone demonstrates that form follows function.[5] This can be demonstrated using a tensegrity model that diagrams the forces vectors passing through bone. If a bone and it's attachments (e.g. the femur) can be described as a tensegrity that interacts with another (e.g. the tibia) then any joint can be seen as the interface between two tensegrities. Taken together they form an articulating tensegrity that is greater than the sums of their individual behaviors. Because the components of tensegrities (compression and tension members) can each be thought of as composed of smaller tensegrities, the body is seen as fractal and hierarchical. The body as a whole is always synergistically involved in the actions of the peripheries. Equally, articulations of successive joints such as fingers, wrist, elbow, shoulder do more than just add up– their effect is multiplied.

## Geometry of the Body

The core of the body, the torso is probably the easiest to model using tensegrity principles. It has bilateral symmetry, oscillates (breathes) and is bounded on all sides by bony structures. Breathing causes the thoracic cage to expand and contract following the pumping action of the diaphragm. By abstracting the shape somewhat it is feasible to map the force vectors of the torso onto an expanded octahedron tensegrity (each of the three axis of the octahedron have been doubled and separated creating a void within).

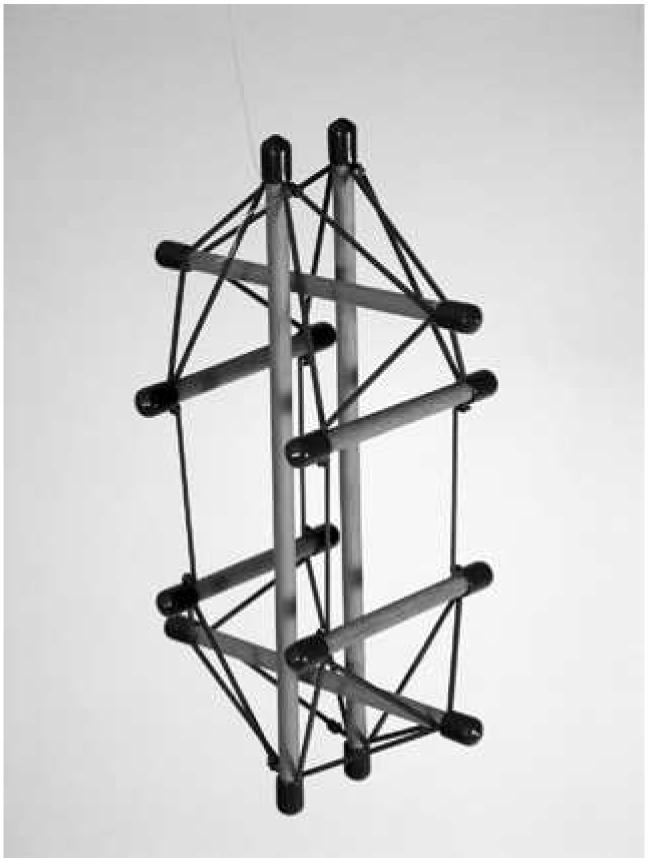

Fig 5. Modified X-Octa Tensegrity

This is one of very few tensegrities that exhibit symmetry in three planes and it is well suited to model the torso. This tensegrity contracts and expands in the same way the torso does and there is a central cavity, as found in the body, created by the geometry. As two parallel struts are pulled apart (equivalent to e.g. the expansion of the ribs) both other parallel pairs counter intuitively expand and pull away from each other as well. When a load is imposed, like a weightlifters body at the moment of a lift, the tensegrtity tightens by rotating down and gets smaller. Built from only six struts (suitably modified) they correspond to the boundary planes of the torso– the transverse planes of the clavicle and the pelvis, the coronal planes of the spine and sternum, and the sagittal planes of the ribs on both sides. As well as these bilateral relationships, the compression members also have eight trilateral associations. As in all tensegrities, the torques generated in the triangular relationships all cancel out. There are eight turbining tensioned triangles, four clockwise and four counterclockwise which correspond to eight sections of the torso. Additionally the range of motion and degrees of freedom of the expanded octahedron tensegrity closely matches the torso. The actual geometry (and anatomy) is more complex but the pattern is discernable. If this is a valid comparison, it is worthwhile to examine the musculature to identify helical rotations in these areas and use the behavior of the model to make predictions.

## Geometry of the Spine

Years ago I noticed a resemblance between individual thoracic vertebrae and stellated tetrahedrons.

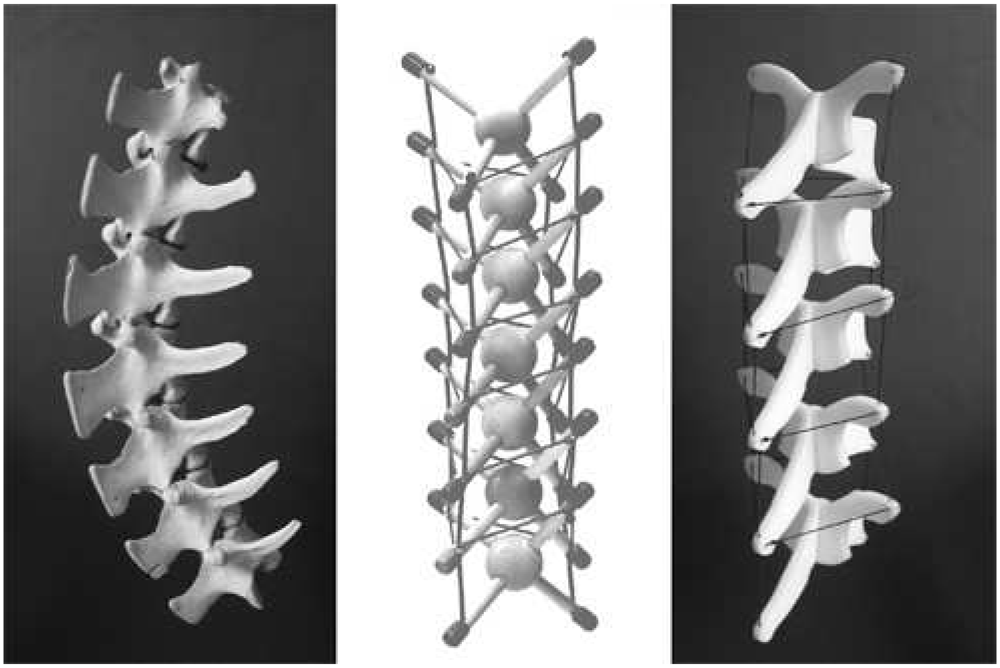

Fig 6. Stellated Tetrahedron Tensegrities

This intrigued me as stacked stellated tetrahedrons can be suspended in a tensile system to form flexible yet stable tensegrity masts. In the vertebrae the angle between the spinous process and the anterior inferior vertebral body form two arms of a tetrahedron; the other two arms are the transverse processes. A tensegrity mast, like the spine functions whether vertically or horizontal and can accept loads in any position.

Fig 7. Tensegrity Spine

The spinous process of a superior thoracic vertebra depends below the transverse processes of an inferior vertebra and may allow for a partial tensegrity suspension. But in the cervical and lumbar vertebrae the geometry is different and harder to envision. The articular facets in the lumbar are angled to support a suspensory load and the nuchal and thoracolumbar fascia may play a part in addition to ligaments and muscles. More analysis is needed to ascertain what part tensegral suspension plays in support of the vertebral array. In any case, the intervertebral discs which act as couplers can also be modeled as tensegrity cushions that can accept and transfer loads.

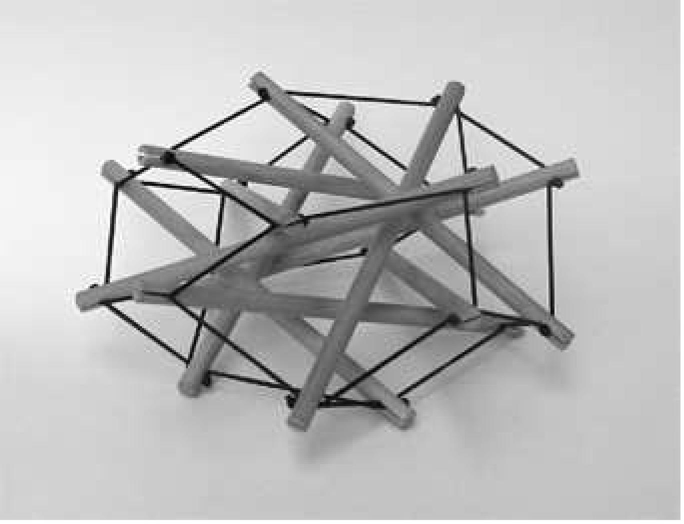

Fig 8. Tensegrity Disc

The vertebral body is also somewhat compressible much like a stiff spring (and can be modeled by tensgrity prisms). Tensegrities upon tensegrities inside larger tensegrities… a model complex enough to describe the actual behaviors of the spine.

## Geometry of the Pelvis

As the pelvis also displays bilateral symmetry, another modified expanded octahedron can be added to the torso to represent the ilia and providing a connection for the femurs.

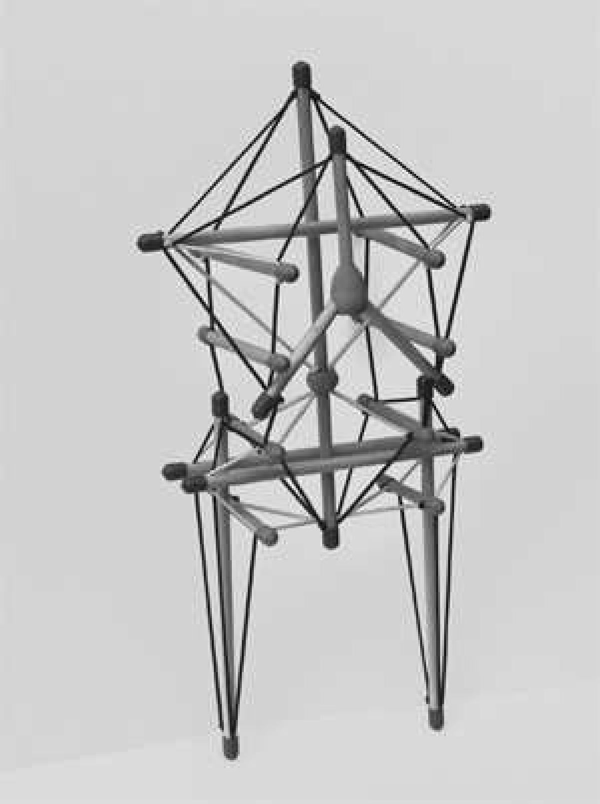

Fig 9. Tensegrity Torso and Pelvis

The pelvis is a complicated structure and this solution is highly abstract. It is oriented along the familiar 'x, y, and z' axis' and is schematic of the pelvis which has equivalent orientations (left/right, top/bottom, front/back). The horizontal struts (x, z) illustrate the dynamic balance of the ilia in relationship to the spine and femurs that are represented by the vertical (y axis) struts.

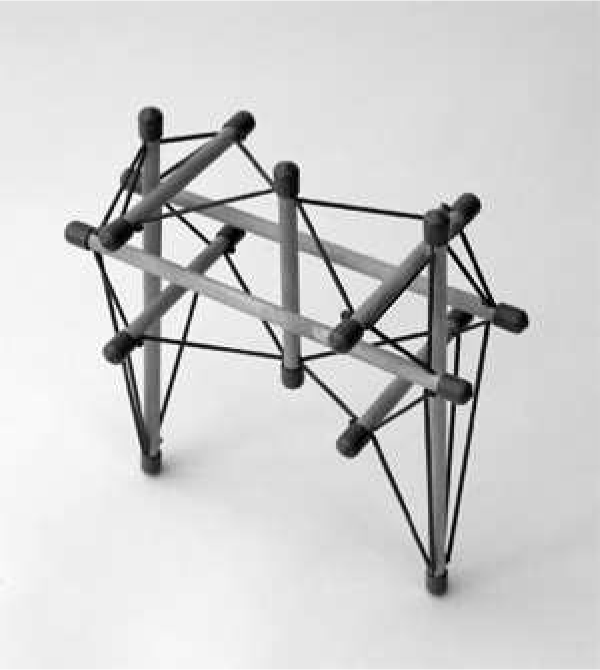

Fig 10. Tensegrity Pelvis Balanced

Pathomechanics of the pelvis and lower back are illustrated by shortening or lengthening individual tension members that are equivalent to hypo- or hyper-tonicity of part of the pelvic musculature. Using this model, it is possible to distort one or more tensile components (ligaments/muscles) and observe the overall effect on the structure.

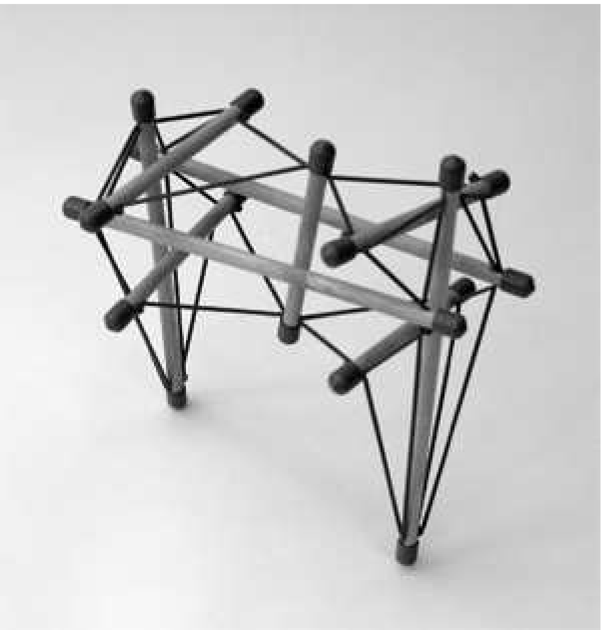

Fig 11. Tensegrity Pelvis Unbalanced

Note that a change of length (or tension) in only one tensile component (e.g. the sacroiliac ligament or pelvic floor) causes distortions to occur throughout the structure in all three axes. This model illustrates that a change in length of a tension component is equivalent to an increase or decrease of mobility in that area of the body.

This model also demonstrates gait. As the femur struts (z axis) articulate, simulating walking, the corresponding torque in the struts (x, y axis') demonstrate the rotation in the ilia. By distorting a single tension element you can then observe the corresponding distortion in gait.

A more complex look at the geometry strongly suggests that the pelvis is organized as an octet truss. Octet trusses are omni triangulated space frames composed of octahedrons and tetrahedrons in a close packing array. It is an extremely strong, lightweight structure that distributes forces along the six axes that form the edges of the linked polyhedra. It has been used extensively in truss–supported roofs for very large buildings but the mechanical advantages are independent of scale.

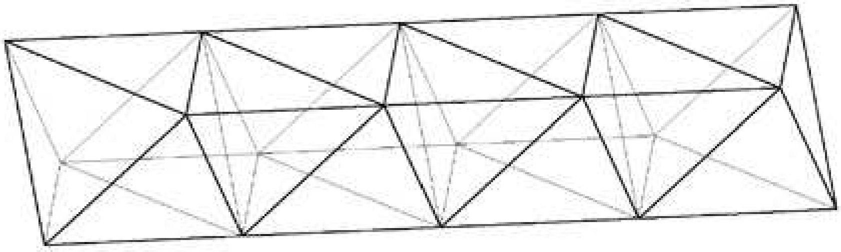

Fig 12. Octet Truss

Each Ilium is a tetrahedron hinged at the pubis and the sacrum. The pubis ramus' and the ischial tuberosity define a triangular plane that is rotated approximately 90 degrees to the plane of the iliac fossa and crest. These planes form a clear tetrahedral relationship. The spacing between the ilia creates an octahedral cavity of which the sacrum forms a face. The remainder of the geometry is filled in with ligaments and muscles of the pelvic floor.

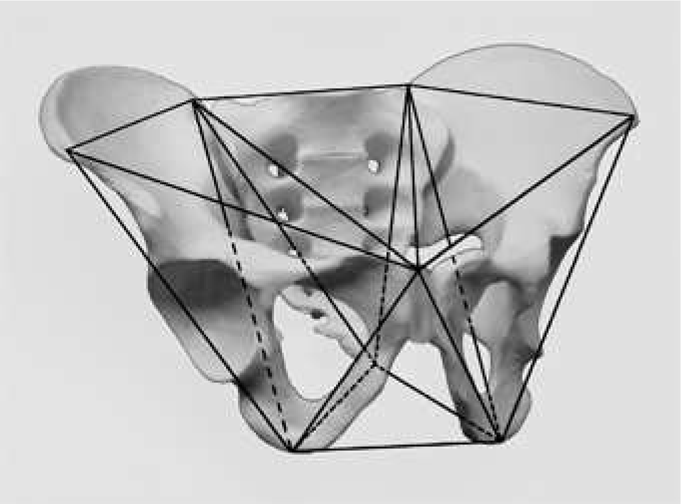

Fig 13. Pelvis Schematic

This is exactly the same relationship that two tetrahedron have to an octahedron in an octet truss.

A tensegrity model of this arrangement can demonstrate the linked yet flexible range of movement in the pelvis and the forces acting through the bones, ligaments and muscles.

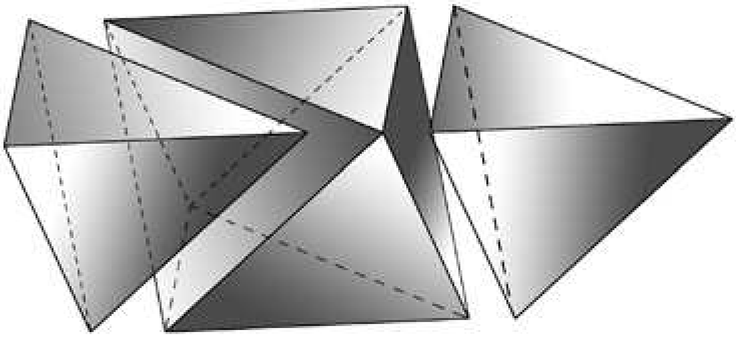

Fig 14. Octet Pelvis

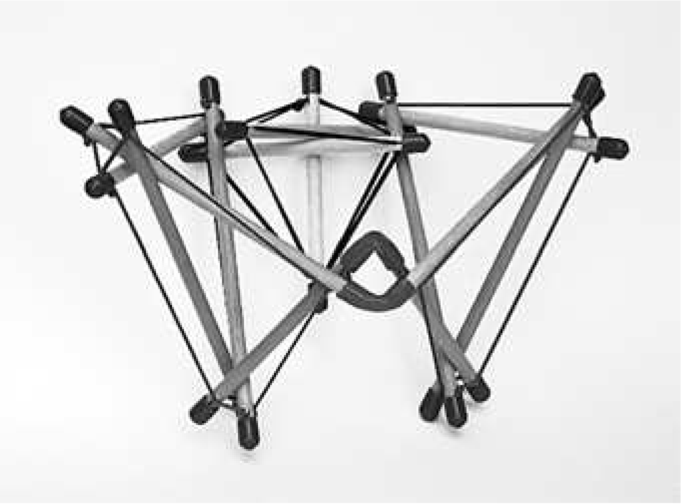

Fig 15. Tensegrity Octet Pelvis

It could be said that geometry describes an arrangement in space and tensegrity shows how it is constructed. As befits their complex character, there is always more than one way to string a tensegrity. In other words this model is an approximation and a best guess. Other solutions to the observed geometry are possible.

## Geometry of a Joint

The attempt to model the range of movement and degrees of freedom of our limbs is the litmus test of the biotensegrity hypothesis. As noted, the traditional definition of tensegrity does not include joints. Further, the prestress can be so high that it is difficult to imagine how a tensegrity joint could be fluid. Kenneth Snelson, who is more than a theoretician, builds tensegrities and understands the problem. He remarked to me that "… with tensegrity it's hard to manage all the prestressed tension lines in order to control motion dynamically in the way our muscles enable all of the bodily swings, rotations, pushes, pulls, and their variations." But there is a way to proceed. Using a (tetrahedral) tension sling it is possible to link discrete tensegrity geometries (as discussed) together to form a universal joint. A tetrahedral 'saddle joint' has two degrees of freedom and a wide range of motion in two planes ninety degrees apart.

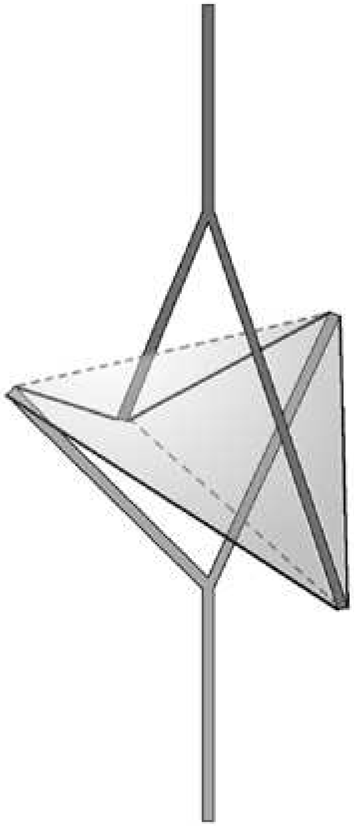

Fig 16. Tetrahedral Saddle Joint

If one degree of freedom is constrained the resultant hinge begins to move like the knee, except it hyper extends both posteriorly and anteriorly. Judicious tweaking of geometry brings the model more in line with knee movement. Close examination of the condyles of the femur and the eminence of the tibia reveals the forces acting upon them and show a plausible saddle relationship that can be modeled as two tensegrities interdigitating.

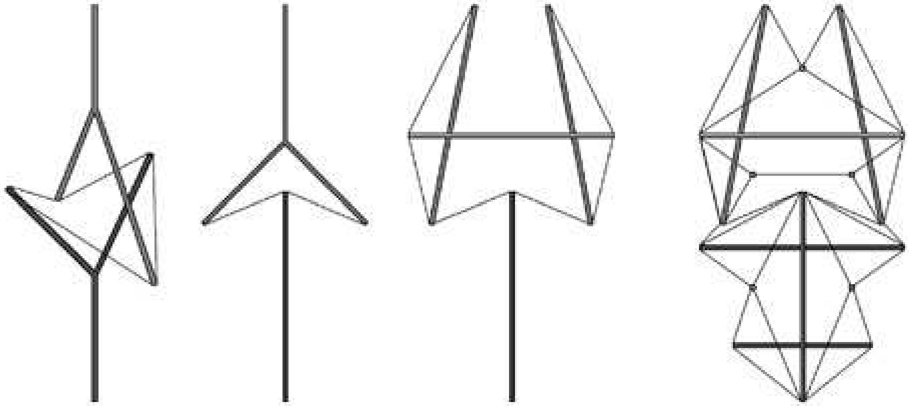

Fig 17. Tensegrity Knee Saddle Joint

Two modified expanded octahedrons rotated 90 degrees to each other axially shows a remarkably close fit to the geometry of the knee.

Fig 18. Tensegrity Knee Construction

In addition the patella is a tetrahedral shaped bone that nests in a gap between the femur and tibia, its position maintained by another saddle tension sling between the condyles of the femur. For the purposes of this simplified model the fibula is considered part of the tensegrity of the tibia.

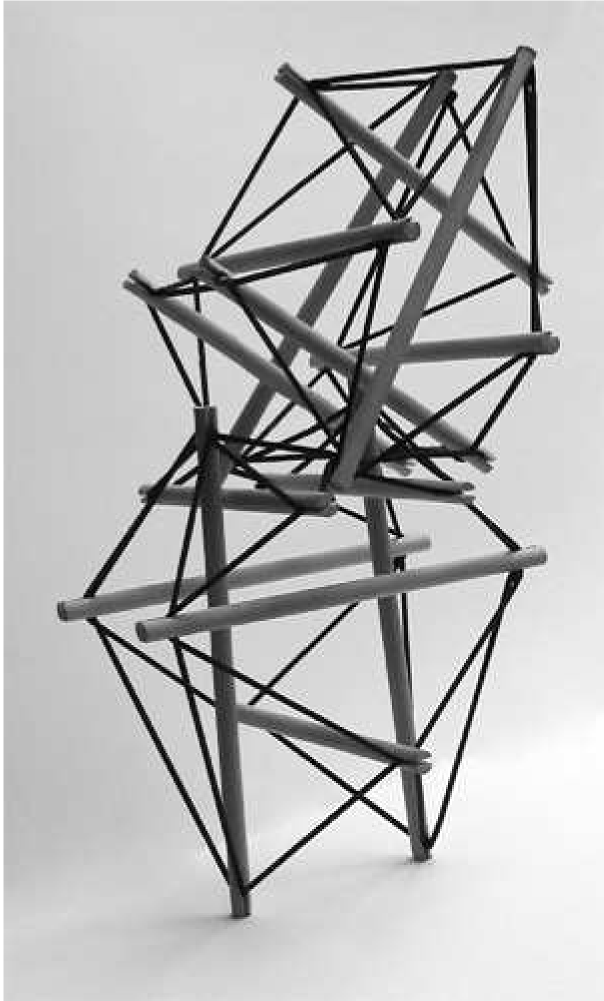

Fig 19. Tensegrity Knee Bent

But how to effect fluid yet controlled movement? Adding a second layer of tension that crosses a joint or joints without being required to carry the entire prestress load, would allow range of movement in an arm or a leg. The prestress of the two tensegrities is not additive and does not cross the joint so it moves freely.

The assumption is that the ligaments and fascia act as deeper layers of tension that carry the prestress and the muscles stabilize (degrees of freedom) but also are free to operate across the interface (range of motion). Again more research is needed.

**Tensegrity prisms**

A class of chiral (mirror image) tensegrities known as T–prisms illustrates helical forces that act like non–linear springs. They can be knitted together in contiguous layers to any length and any girth.

Fig 20. Spiral Tensegrity Mast

Fig 21. Tensegrity Foot Construction

Clockwise or counterclockwise, single layer, fourfold T–prisms are appropriate to describe the weight transfer from the leg to the foot. The talus distributes the loading both posteriorly onto the calcaneus and anteriorly onto the navicular and other tarsal bones. The geometry of T-prisms is similar: it makes a credible shock absorber and the helical rotation as it compresses, mimics the pronation of footfall. Stored energy is then released as it expands providing rebound.

They compress along the vertical axis because their triangulation is hybrid and incomplete, (partly compressive and partly tensile) but can be strengthened by adding components to add any degree of stiffness.

## What next?

I've tried to convey some of the inner workings of tensegrities in this cursory look at applying Biotensegrity to the geometry of anatomy. My observations and ideas are speculative and my models approximate; more needs to be done to fill in the details. As the investigation is just beginning, I am interested in how this will be received over time in the larger medical community. Owing to the power of the idea and thanks to the writings and presentations of Fuller, Snelson, Ingber, Levin and many others, it appears certain that tensegrity ideas are going to influence the next generation of scientists and artists. My intent is to provide some of the means to further the discussion along productive and scientific lines. I do not pretend to be doing science; rather I'm laying out the groundwork for future scientific research and investigations. Ultimately if it is a good fit, I would expect to see existing and future healing methodologies incorporating the insights and strengths of tensegrity in their techniques and applications.

New biotensegrity iterations are under way and I invite interested people to contact me with their comments and suggestions. Studies include explorations into related fields such as prosthetic design, exoskeletons, and robotics. The advantages of tensegrities are so obvious (strength, resilience, weight) that I expect they will play a key role in future advances in these and other technologies.

Final note: even as bodies are treated as wholes, so they are embedded in their social and physical matrix and play their parts in the skein of a larger tensegrity community. But that's for Carlos Castenada and Stafford Beer to sort out...

1. Salvadori, Mario, 1980, Why Buildings Stand Up, Norton, pp 83–84

2. Wikipedia, http://en.wikipedia.org/wiki/Tensegrity

3. Fuller, R. Buckminster, 1975, Synergetics, Macmillan, pp 372

4. Kenneth Snelson, Interview,
http://www.kennethsnelson.net/faqs/faq.htm#1

5. Netter, FH, 1987, Volume 8 Musculoskeletal System, pp 187