The Importance of Soft Tissues for Structural Support of the Body

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Most of us view the skeleton as the frame upon which the soft tissues are draped. The post-and-beam construction of a skyscraper is the favored model for the spine[13] and is used for all biologic structures, as the upright spine is regarded as the highest biomechanical achievement. The soft tissues are regarded as the curtain walls of steel-framed buildings or possibly as stabilizing "guy wires" (FIG. 1).

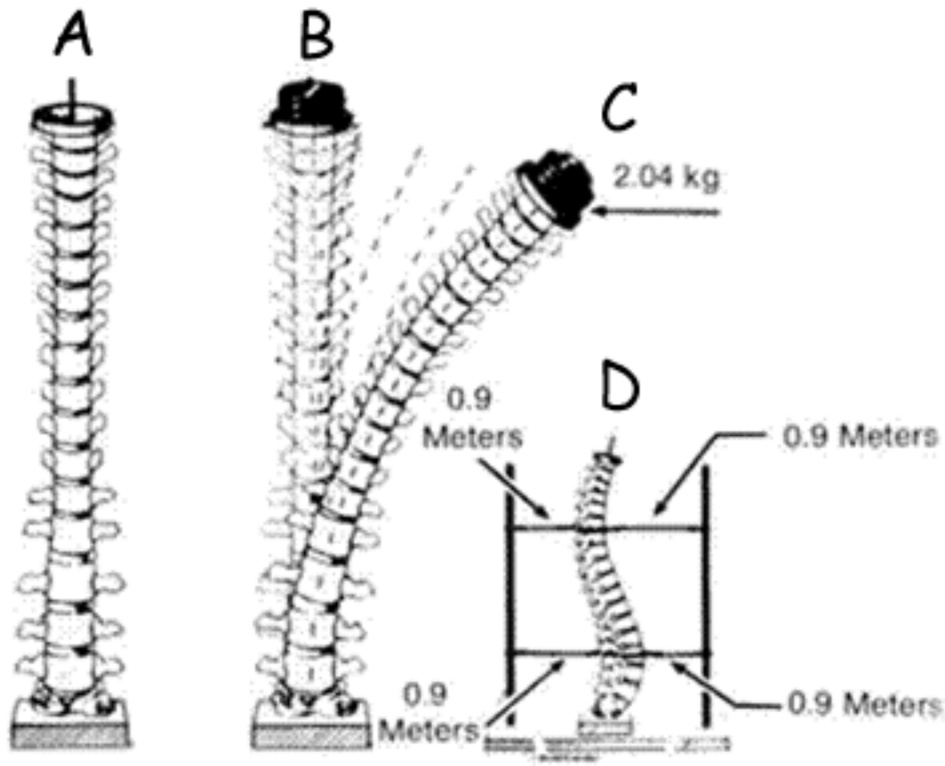

Fig. 1.
thoracolumbar spine, fixed at the base and free on top, under vertical loading and restrained at mid thoracic and midlumbar levels in the anterioposterior plane. **A,** before loading. **B,** during loading. **C,** stability failure occurring under a load of 2.04 kg. **D,** lateral view showing restraints. *(From Morris JM, Markolk KL:Biomechanics of the lumbar spine:In American Academy of Orthopedic Surgeons :Atlas of Orthotics. St. Louis, Mosby, 1975: with permission.)*

Skyscrapers are immobile, rigidly hinged, high energy consuming, vertically oriented structures that depend on gravity to hold them together. The mechanical properties are Newtonian, **Hookian** and **linear**. [5,7] A skyscraper's flagpole or any weight that cantilevers off the building creates a bending moment in the column that produces instability. The building must be rigid to withstand even the weight of a flag blowing in the wind. The heavier or farther out the cantilever, the stronger and more rigid the column must be (FIG. 2).

Fig. 2. Bending stresses in a beam.
(From Galileo: discorsi a demonstrazioni matematiche intorno a due nuove scienze. Leiden, 1638.)

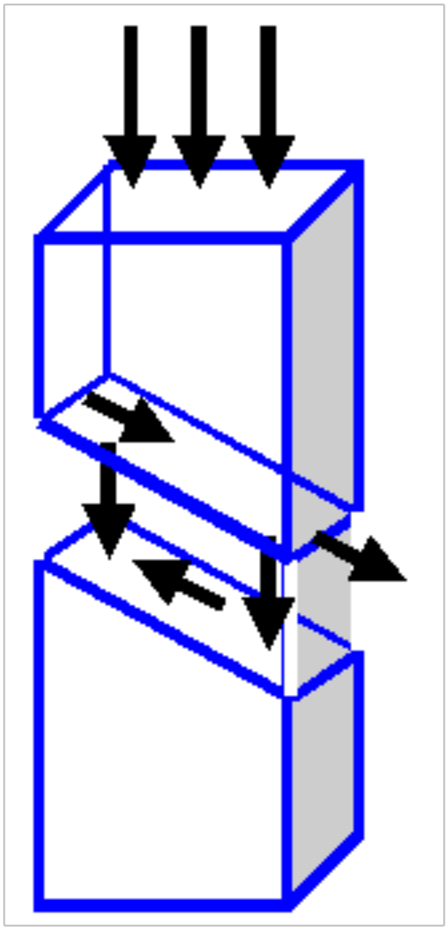

Fig. 3. when simple compressive load is applied, both compressive and **shear stress** must exist on planes that are oriented obliquely to the line of application of the load.

A rigid column is necessarily base-heavy to support the incumbent load. The weight of the structure produces internal shear forces that are destabilizing and require energy just to keep the structure intact (FIG. 3).

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[6]. If a human skeletal system functions as a **lever**, then reaching out a hand or casting a fly at the end of a rod is impossible (FIG. 4). The calculated forces with such acts break bone, rip muscle, and deplete energy.

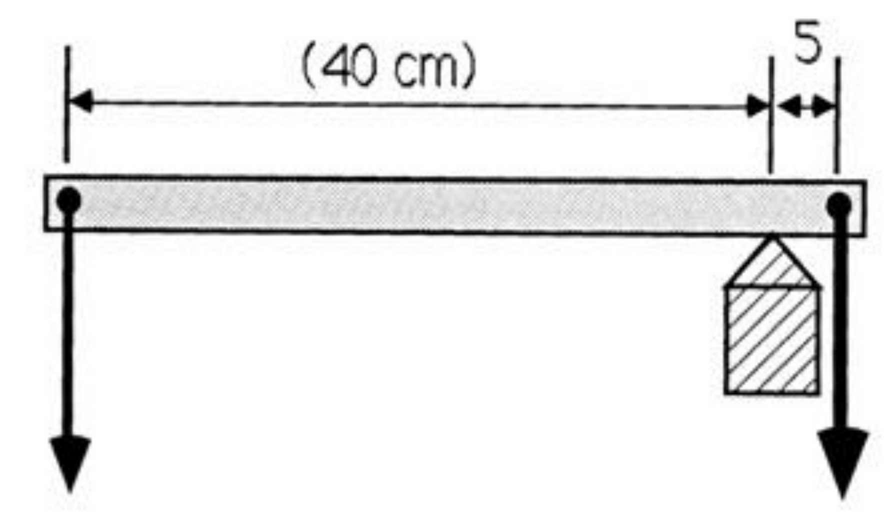

Fig. 4. A load of 200 kg, (not unusual for a trained weight lifter), located 40 cm from the fulcrum requires a muscle reaction force of 8 x 200 = 1600 kg. The *erectores spiae* group can generate a force of about 200 to 400 kg, a force of only one quarter to one half of that necessary. Even a weight of 25 kg would put an average man at risk of tearing his back muscles. Muscle power alone cannot lift moderately heavy loads close to the body or light loads extending out from the body, such as a fish on the end of a rod.

A post-and-beam model cannot be used to model the neck of a flamingo, the tail of a monkey, the wing of a bat or the spine of a snake (Fig, 5). As there are no bones in invertebrates there is no satisfactory model to adequately explain the structural integrity of a worm. Post-and-beam modeling in biologic structures could only apply in a perfectly balanced, rigid hinged, upright spine (Fig 6). Mobility is out of the equation. The forces needed to keep a column whose center of gravity is constantly changing and whose base is rapidly moving horizontally are overwhelming to contemplate. If we add that the column is composed of many rigid bodies that are hinged together by flexible, almost frictionless joints, the forces are incalculable[2]. The complex cantilevered beams of horizontal spines of quadrupeds and cervical spines in any vertebrate require tall, rigid masts for support[2] that are not usually available.

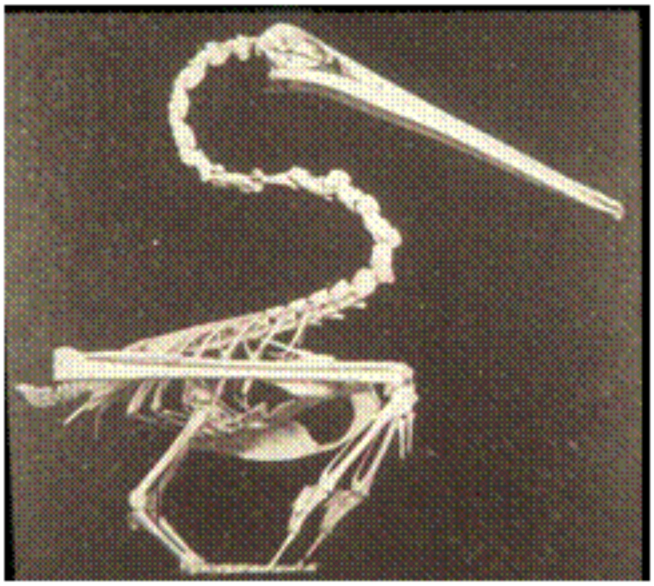

Fig. 5. Bird skeleton. *(Courtesy of California Academy of Sciences, San Francisco.)*

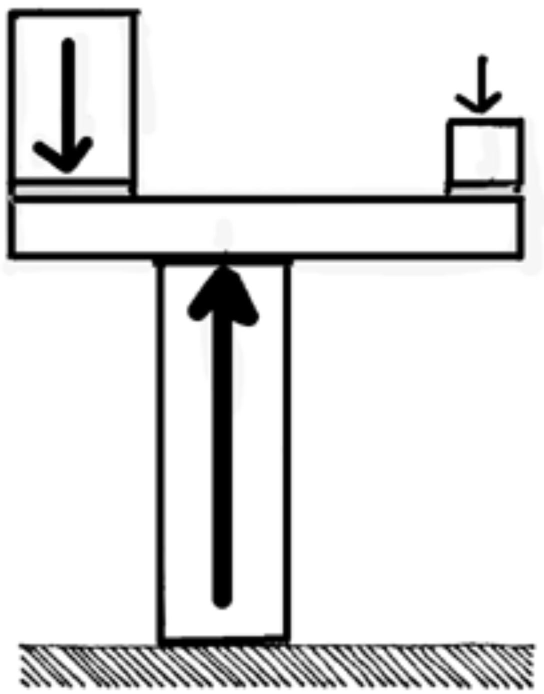

Fig. 6. Balancing compressive loads.

Since post-and-beam construction has limited use in biologic modeling, other structural models that exist must be explored to see if a more widely applicable construct can be found. Thompson[16] and, later, Gordon[5] use a **truss system** similar to those used in bridges for modeling the quadruped spine. Trusses have clear advantages over skyscraper post-and-lintel construction as a structural support system for biologic tissue. Trusses have flexible, even frictionless hinges with no bending moments about the joint. The support elements are in tension and compression only. Loads applied at any point are distributed about the truss, as tension or compression (Fig.7). In post-and-beam construction, the load is locally loaded and creates leverage. There are no levers in a truss and the load is distributed through the structure. A truss is fully triangulated and is inherently stable. They cannot be deformed without producing large deformations of individual members. Since only trusses are inherently stable with freely moving hinges, it follows that any structure that has freely moving hinges, but is structurally stable, must be a truss. Vertebrates that have flexible joints must therefore be constructed as trusses.

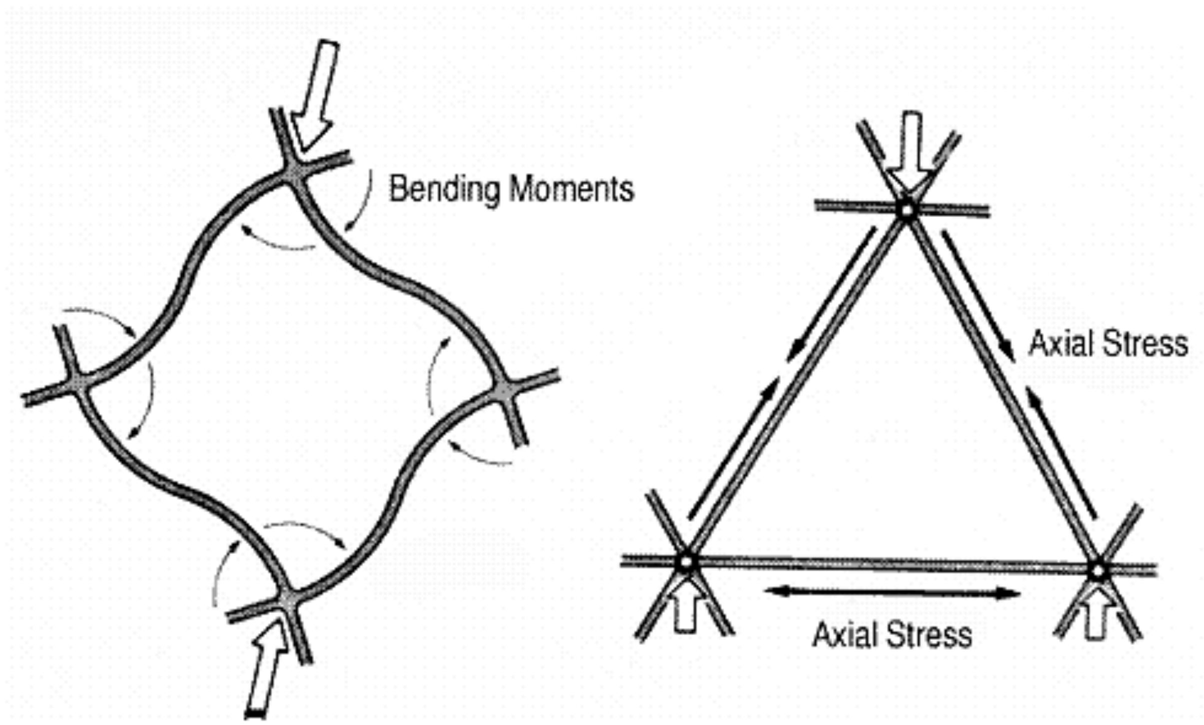

Fig. 7. Loading a square and loading a triangular truss.

When the tension elements of a truss are wires or ropes, the truss usually becomes unidirectional (Fig, 7), as the element that is under tension will be under compression when turned topsy-turvy. The tension elements of the body (the soft tissues—fascia, muscles, ligaments, and connective tissue) have largely been ignored as construction members of the body frame and have been viewed only as the motors. In loading a truss the elements that are in tension can be replaced by flexible materials, such as ropes, wires, or in biologic systems, ligaments, muscles, and fascia. The tension elements then are an integral part of the construction and not just a secondary support. However, ropes and soft tissue can only function as tension elements and most trusses constructed with tension members will only function when oriented in one direction. They could not function as mobile, omni-directional structures necessary for biologic functions. There is a class of trusses, termed "**tensegrity**" [3] structures, which are omni-directional so that the tension elements always function in tension no matter what the direction of applied force. A wire cycle wheel is a familiar example of a tensegrity structure. The compression elements in tensegrity structures "float" in a tension network just as the hub of a wire wheel is suspended in a tension network of spokes.

To conceive of an evolutionary system construction of tensegrity trusses that can be used to model biologic organisms, we must find a tensegrity truss that can be linked in a hierarchical construction. It must start at the smallest sub-cellular component and must have the potential, like the beehive, to build itself. The structure would be one integrated tensegrity truss that evolved from infinitely smaller trusses that could be, like the beehive cell, both structurally independent and interdependent at the same time. **Fuller**[3] and **Snelson**[15] described the truss that fits these requirements, the tensegrity icosahedron. In this structure, the outer shell is under tension and the vertices are held apart by internal compression "struts" that seem to float in the tension network (Fig. 8D).

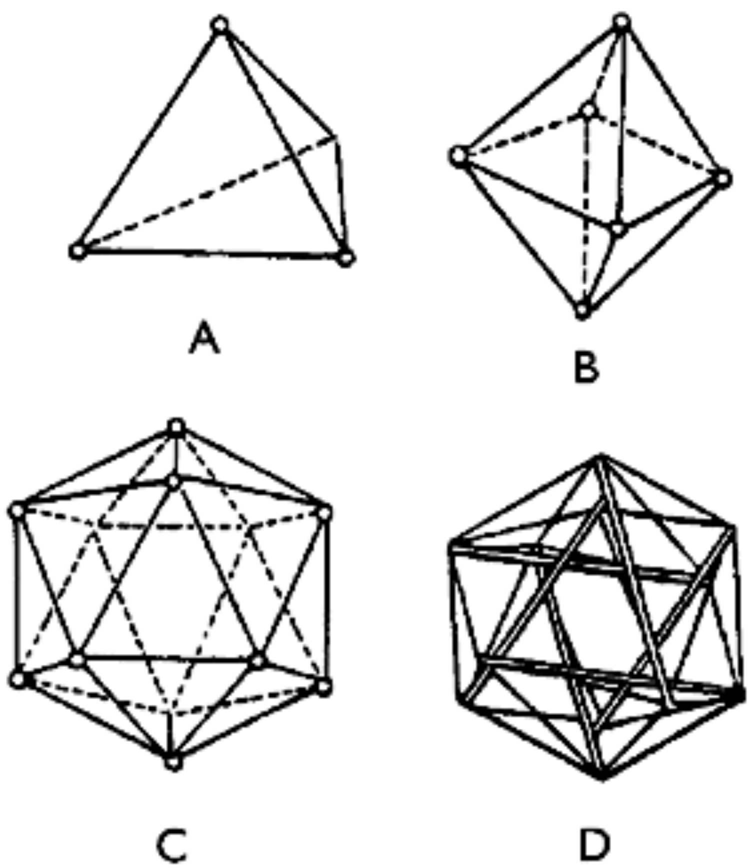

Fig. 8. A. **tetrahedron**. B. **octahedron**. C. **icosahedron**. D. **tension-vectored icosahedron** with compression elements within the tension shell. The compression elements do not "press" on one another but are fixed in position by the tension network. These, and their hierarchical constructs, are the only structures that are stable, by virtue of their architecture, in three-dimensional space.

The tensegrity icosahedron is a naturally occurring, fully triangulated, three-dimensional truss. It is an omni directional, gravity independent, flexible hinged structure whose mechanical behavior is **non-linear**, **non-Newtonian** and non-**Hookean**. Fuller and Snelson independently use this truss to build complex structures. Fuller's familiar **geodesic dome** (fig. 9.) is an example, and **Snelson**[14] has used it for artistic sculptures that can be seen around the world. **Ingber**[9,18] and colleagues use this model as the bases of cell construction. There is research underway to use this structure in more complex tissue modeling.[18] Naturally occurring examples that have already been recognized as icosahedra are the self-generating "fullerenes" **carbon$_{60}$** organic molecules[10], **viruses**[19] (fig. 10), clethrins[1], cells[17], **diatoms**, **radiolaria**[8], pollen grains, dandelion balls a variety of fruits such as raspberries and sweetgum, blowfish and several other biological structures.[11]

Fig. 9. Geodesic Dome, Vancouver BC

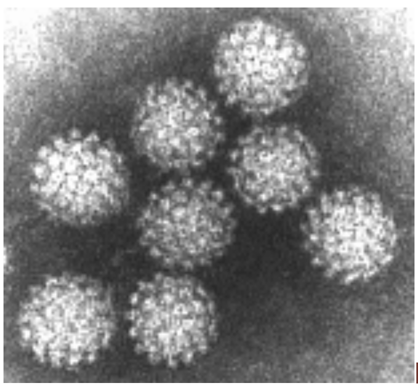

Fig. 10. **Viral Architecture**. Linda Stannard, U of Cape Town. A "must read" website that gives structural explanations for the icosahedron - viral relationship.


Fig. 11. Dandelion.


Fig. 12. Sweetgum seed pod.

Fig. 13. Fat cells **closest packed** containing globules of fat that are closest packed.


Fig. 14. Spiney Pufferfish.

Icosahedra are stable even with frictionless hinges and, at the same time, can easily be altered in shape or stiffness merely by shortening or lengthening one or several tension elements. Icosahedra can be linked in an infinite variety of sizes or shapes in a modular or hierarchical pattern with the tension elements, (the muscles, ligaments, and fascia), forming a continuous interconnecting network and with the compression elements, (the bones), suspended within that network (fig. 13). The structure would always maintain the characteristics of a single icosahedron. A shaft, such as a spine, may be built that is omni-directional and can function equally well in tension or compression with the internal stresses always distributed in tension or compression. There are no bending moments within a tensegrity structure and, therefore, they have the lowest energy costs.

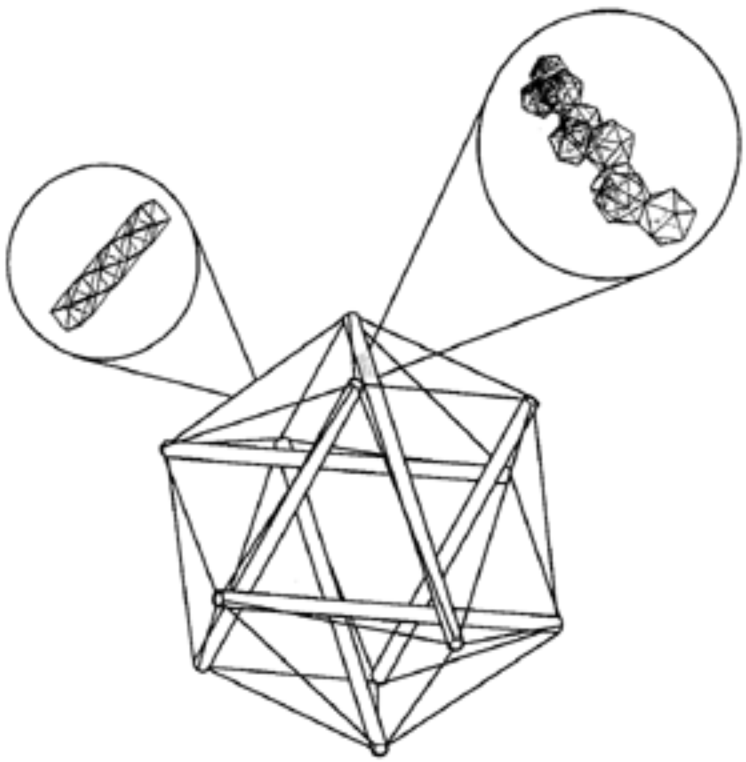

Fig. 13. Hierarchy of tensegrity icosahedrons.

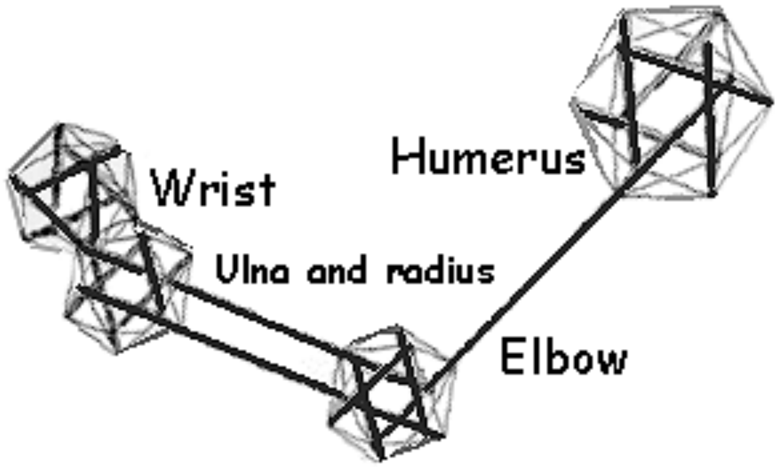

Fig. 14. Tensegrity arm.

Viewed as a model for the skeletal system of any vertebrate species, the tension icosahedron space truss, with the bones acting as the compressive elements and the soft tissues as the tension elements, will be stable in any position, even with multiple joints. They can be vertical or horizontal and assume any posture from ramrod straight to sigmoid curve or any position or configuration in between (FIG.15). Shortening one soft tissue element has a rippling effect through the structure. Movement is created and a new, instantly stable, shape is achieved. It is highly mobile, omni-directional, and low energy consuming. It is a unique structure that when used as a biologic model the constructs would conform to the natural laws of least energy, laws of mechanics, and the apparent peculiarities of biologic tissues. The icosahedron space truss is present in biologic structures at the cellular, sub-cellular, and multi-cellular levels. The icosahedron is presently used in modeling viruses, radiolarians, sub-cellular organelles, and whole organisms. The very building block of bone, hydroxyapetite, is an icosahedron. In the spine, each subsystem (the vertebra, the disc, the soft tissues) would be subsystems of the spine meta-system. Each would function as an icosahedron independently and as part of the larger system, as in the beehive analogy.

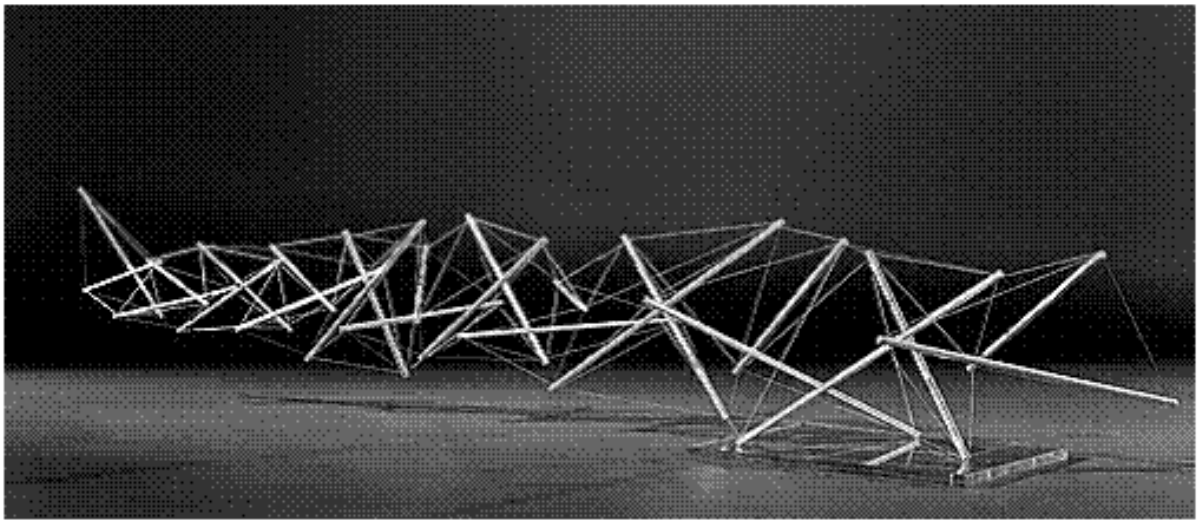

Fig. 15. *Easy-K,* 1970 - aluminum & stainless steel
10 x 10 x 58 inches
25 x 25 x 147 cm
Exhibition: Sonsbeek '70, Arnhem, Holland,
With permission of **Kenneth Snelson** (Click the link then "Sculpture". See them all and make certain you see the QTVR 3-D versions.)

The icosahedron space truss spine model is a universal, modular, hierarchical system that has the widest application with the least energy cost. As the simplest and least energy consuming system, it becomes the meta-system to which all other systems and subsystems must be judged and, if they are not simpler, more adaptable, and less energy consuming, rejected. Since this system always works with the least energy requirements there would be no benefit to nature for spines to function sometimes as a post, sometimes as a beam, sometimes as a truss, or to function differently for different species, conforming to the minimal inventory-maximum diversity concept of Pierce[12] and evolutionary theory.

The icosahedron space truss model could be extended to incorporate other anatomic and physiologic systems. For example, as a "pump" the icosahedron functions remarkably like cardiac and respiratory models and so, may be an even more fundamental meta-system for biologic modeling. As suggested by Kroto[10], the Icosahedron template is "mysterious, ubiquitous, and all-powerful."

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