A suspensory system for the sacrum in pelvic mechanics: Biotensegrity

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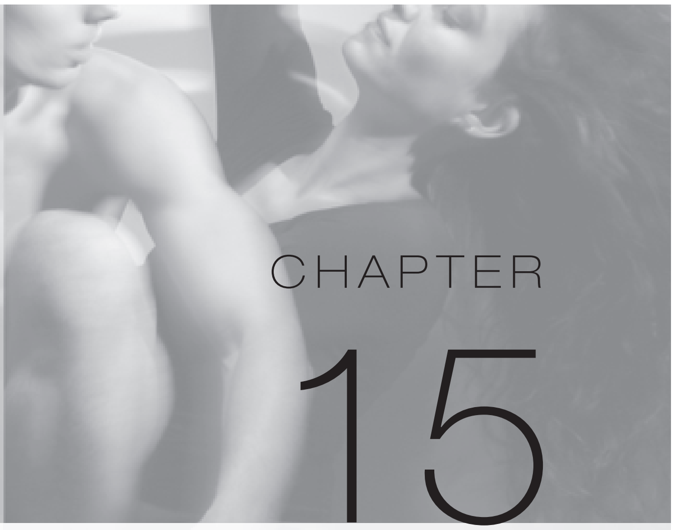

CHAPTER

15

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S. M. Levin

The paradigm

According to conventional wisdom, the human spine behaves as an architectural column or pillar and transfers the superincumbent weight through the sacrum, to the ilium, through the hips and down the lower extremities. The pillar holds the base in place with the pressing weight of gravity. In this model, the sacrum, as the base, locks into the pelvis, either as a wedge or by some other gravity-dependent closure.

In a tensegrity model as applied to biologic structures – biotensegrity – the bones of the skeleton are not considered a supporting column but compression elements enmeshed in the interstices of a highly organized tension network. The bones, including the sacrum, 'float' in this network much like the hub of a wire spoke cycle wheel is suspended in its tension-spoke network.

The anomalies

Architectural pillars orient vertically and function only in a gravity field and are rigid, immobile, base heavy, and unidirectional. Pillars and columns resist compression forces 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 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 (Morris & Lucas 1964) and the vertebral bodies would crush under the leverage of a fly rod held in a hand. Animals larger than a lion would continually break their bones, and dinosaurs and mastodons larger than a present-day elephant would have been crushed under their own weight. Urinary bladders and pregnant uteri would burst when full and, with each heartbeat, arteries would lengthen enough to crowd the brain out of the skull (Gordon 1978).

Although it is a teleological conceit that the human spine acts as a column, phylogenetic and ontogenetic development of the human spine was not in the form of a column, but as some form of a beam. It would not be an ordinary beam – a rigid bar –but an extraordinary beam composed of rigid body segments connected by flexible connective tissue elements that floated the segments in space (Fielding et al 1976). During human gestational development and during the first year or so of life, when a child does no more than crawl, the human spine does not function as a column but as such a beam. In many postures the human spine does not function as a column or even a simple beam. When the spine is horizontal, as when crawling or swimming, the sacrum is not a base of a column but the connecting element that ties the articulated beam to the pelvic ring. Even when upright, the vertebral blocks are not fixed by the weight of the load above, as they would be in an architectural pillar. S-shaped curves can create intolerable loads and instability in a column, particularly if it is an articulated column that has flexible, near-frictionless joints, as does the spine. With each breath, the interconnected vertebrae translate, some forward, some backward. Whereas 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. The spine can bend forward so people can touch their toes and bend backward almost equally well. It can twist and bend simultaneously. It can perform intricately controlled movements in space, as in gymnastics, dance, aquatic diving, or basketball. The spine is flexible, mobile, functionally independent of gravity, and has property behavior inconsistent with an architectural column or beam.

In all studies, the spine, unlike columns and beams, is a low energy consumer. The individual components of the spine, and indeed the structure as a whole, behave non-linearly and do not conform to the standard linear Newtonian mechanical laws that govern columns and beams (Fox 1988, Panjabi & White 2001). In an attempt to make complex problems simple, bioengineers have converted non-linear complexities to linear mathematics models. This misrepresents the true nature of the structures.

The alternative

If, instead of a column, consider the spine to be a series of rigid bodies, like a beaded chain. Just as the beads are connected by tensioned wires, so the vertebrae are tied together by the discs and soft tissues. The sacrum is the connecting link to the pelvis, but what locks the sacrum in place so that the spine is supported in all its functions? An omnidirectional mechanical system exists that can function in any posture and be capable of transferring considerable loads, coming from any direction, through the pelvis and to the lower extremities. Such a system must be consistent with evolutionary theory. It must also be structurally hierarchical so that in any instant in its ontological development it is mechanically functional and stable. (Embryos and fetuses do not fall apart either in or out of the womb.)

Kinematics

The kinematics of the pelvis must take into account mechanical laws that affect a free body in space. A rigid body in space is described as having six degrees of freedom of movement in a three-dimensional Cartesian coordinate system. (Fig. 15.1) However, although in classical mechanics there are six degrees of freedom, others have considered that describing twelve degrees of freedom – six positive and six negative – might be more useful. This system seems suitable for describing the complex movements of the sacrum. Before we can discuss the dynamics of the sacrum or any other structure, we should understand the statics of that structure. How is the sacrum stabilized in its position in the body?

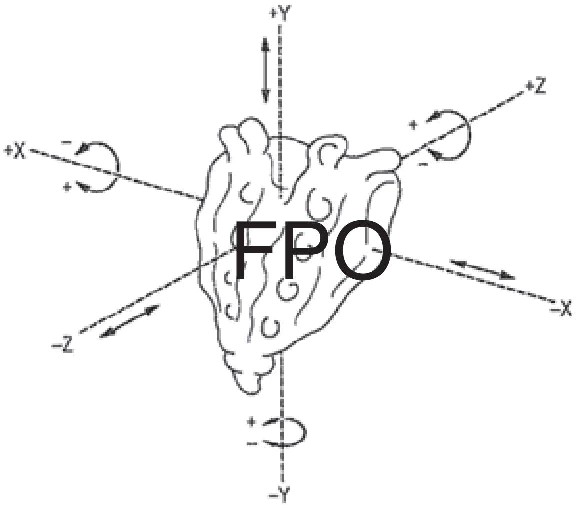

Fig. 15.1 The sacrum in a three-dimensional Cartesian coordinate system. A body can be described as rotating around the three axes, X, Y and Z, in one direction, positively (+), or the other, negatively (–). It also can be described as translating (+) or (–) in the XY, XZ, or YZ planes. A body free to move in any direction is characterized as having 12 degrees of freedom.

Statics

To fix in space a body that has twelve degrees of freedom, it seems logical that there need to be twelve restraints. Fuller (1975) proves this (Fig. 15.2). This principle is demonstrated in a wire-spoke bicycle wheel. A minimum of twelve tension spokes rigidly fixes the hub in space (anything more than twelve is a fail safe mechanism) (Fig. 15.3). In a bicycle wheel, tension-loaded spokes transmit compressive loads from the frame and the ground. The hub remains suspended in its tension network and the compression loads distribute around the rim. The compression elements are discontinuous and behave in a counterintuitive way. Rather than becoming the primary support elements of the system, as they would be in a pillar or wagon wheel model, the compression elements become secondary to the tension support network. Fuller (1975) calls these structures ‘tensegrity’ structures, a contraction of ‘tension integrity’. Tensegrity structures transmit loads through tension and compression only. Because they are fully triangulated, there are no bending moments in these structures, nor is there shear. The most frequently used model of the pelvis conceives of the sacrum as a ‘keystone’ of a Roman arch wedged between the wings of the ilia. Anatomists have long recognized that the sacrum hangs from the ilia by its ligaments (Grant 1952, Kapandji 1977) (Fig. 15.4). Dijkstra (see Chapter 20) and DonTigny (see Chapter 18) illustrate this anatomic configuration. Rather than being a ‘keystone’ in a Roman arch, the sacrum is the reverse of a keystone with the

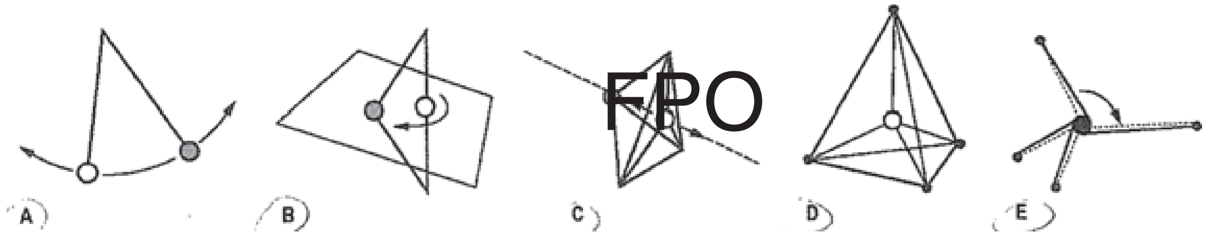

Fig. 15.2 Fixing a point in space. Four vectors of restraint define a minimum system in which a point is fixed in space (D). However, turbining is still possible (E). An additional eight restraints are needed to rigidly fix a point. (Adapted from Fuller 1975.)

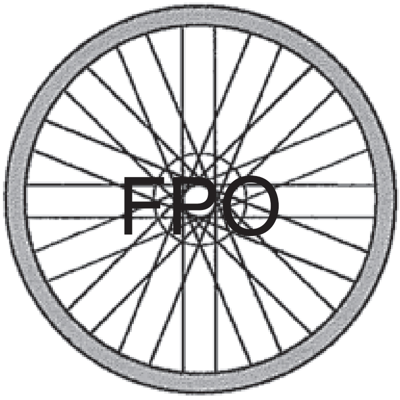

Fig. 15.3 A wire-spoke cycle wheel. The hub is rigidly fixed in a tension network. The compressive load applied to the hub by the weight of the load is transferred to the rim solely through tension. The load distributes evenly around the rim. The bicycle frame and its load hang from the hubs like a hammock between trees.

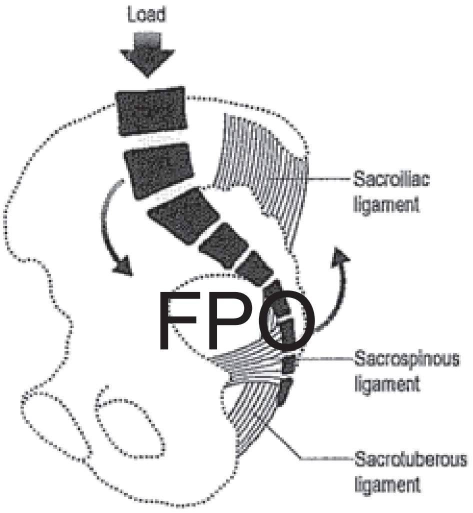

Fig. 15.5 The sacrum suspends in the pelvic ring by its many ligaments. Motion is restricted by the balanced tension of these ligaments.

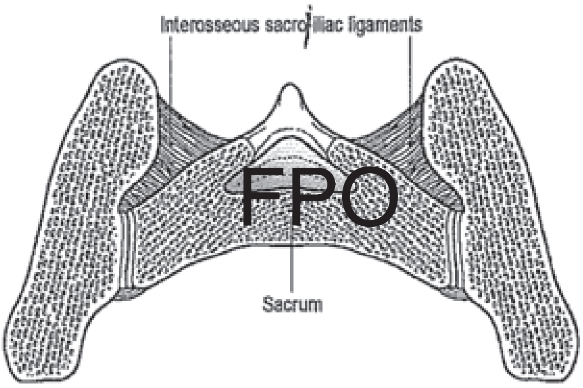

Fig. 15.4 The sacrum suspended from the ilia by the interosseous sacroiliac ligaments. (From Grant 1952, p 340.)

articular surfaces of the sacrum farther apart in front than they are behind, which would allow the sacrum to sink into the pelvis. It is as if the sacrum was hanging on the undersurface of a slippery rock face. The small ridges and rough surfaces described at the articular interface could not keep it from falling. Arches are unidirectional and depend on gravity to hold everything in place. The whole concept of an arch falls apart when a biped stands on one leg. The 'arch' becomes a cantilever with completely different mechanics than a weight-bearing arch. Form fit is not an option in a cantilever. Force fit will require exceedingly high friction and huge musculoligamentous forces that are, in addition to being exceedingly inefficient, not available in the pelvic constructs of vertebrates.

A ligamentous tension system for support and stability is consistent with the known anatomy. If we use a bicycle wheel tensegrity structure as our model for the pelvis, the pelvic ring would be the rim and the sacrum would be the hub of the pelvis. The many tension elements of ligaments and muscles attached to the sacrum stabilize it (Fig. 15.5). The sacrum suspends as a compression element within the musculoligamentous envelope and transfers its loads through that tension network. Even when a person stands on one leg, the sacrum sits within its tension network. This tension network provides omni directional structural stability, independent of gravity and hierarchical. The rim could distribute its load, rather than locally loading the forces at a point.

In a tensegrity system, the forces generated at the hip would not concentrate in the acetabulum but be efficiently distributed throughout the rim, the pelvic bones and soft tissue. The sacrum would remain suspended in its soft tissue envelope (Willard 1995; also see Chapter 1) and transmit the loads above and the forces below through the pelvic ligaments and muscles. Suspended in its tension network, it does not require gravity to hold it in place, as does a keystone model. The tensegrity-modeled sacrum functions right side up, upside down, or sideways. A tension-fixed sacrum works equally well for the upright or space-walking human, the horizontal horse, the flying bat, or the swimming otter. It is the most widely adaptable, and therefore the most likely, pelvic model.

Dynamics

As a hub suspended by its spokes, the tension system must have a dynamic balance of the tension structures. A load on the wheel hub does not change its relative position within the rim. If the tension of the spokes remains constant and the spokes do not distort, the hub does not move at all. Ligaments of the body, likewise, have a high tensile strength and do not distort much when loaded. Assuming a minimum of properly vectored restraints, as with the bicycle model, the sacrum cannot translate or rotate in any direction. It is fixed in position as is the hub of a wheel. Some of the restraints would have to be altered to allow pistoning or rotation to occur. However, if the sacrum moves in tandem with the other bones of the pelvis, so that the ligaments remain at the same length, tension-coupled movement patterns occur.

The body does have this coupled movement option available. It is present in the double tie bar hinge mechanism that is the model for the dynamics of knee movement (Dye 1987, Muller 1983) This type of movement occurs in the 'Jacob's ladder' (Fig. 15.6), an old children's toy. This is a series of tiles connected by crossed ribbons under tension. Flipping one of the tiles creates a controlled tumble. If the end tiles are held apart so that the entire structure is held in tension, the coupled tumbling can occur from top to bottom, bottom to top or sideways. This crossed ligament pattern, clearly evident in the knee, also exists in the spine, at the disc, ligament, and muscle level (Gracovetsky 1988, Kapandji 1977). It explains the coupled motion observed in the spine (White & Panjabi 1978). It is also evident in other joints, such as the capsular ligaments of the hip and the crossed patterns of ligaments and muscles of the back. This crossed tie bar pattern is present at the sacroiliac joints (SIJs) with the crossing patterns of the numerous muscles and soft tissues of the pelvis–spine–hip complex well described in several other chapters of this book. The crossed tie bar mechanism at the SIJ would account for the 'click-clack' phenomenon of the sacrum recognized by Snijders et al (1997). By rotating the ilia, as we do when we walk, the sacrum is forced to tumble and the movement transmits, Jacob's ladder-like, up the spine and to the limbs. Both the static and the dynamic mechanics of the pelvic structures are explained with tensegrity modeling.

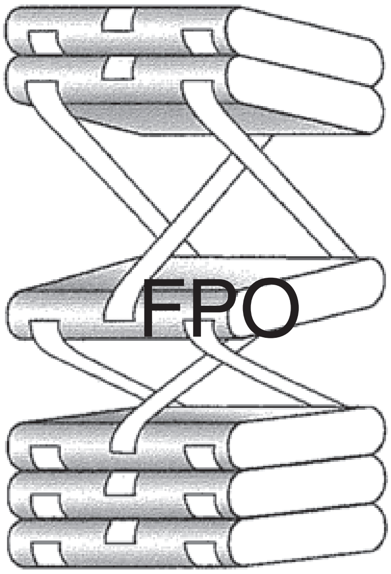

Fig 15.6 Jacob's ladder. Tilting a rigid tile at one end creates a controlled tumble of the other tiles by a crossed tie bar mechanism. The ties remain of the same length and tension throughout the movement.

The evolution of the structure

To fully understand pelvic mechanics and its integration in body mechanisms, it must be placed in its proper context. The tensegrity pelvic system is not creationist in design but is created by the physics of evolution (Fox 1988, Levin 1982, 1986, Prigogine & Stengers 1984). For a biologic structure to exist as an entity it must be inherently stable and self-contained, not only when fully developed, but also at each instant of its existence. Only triangulated structures are inherently stable (Pearce 1978). Structures that are not fully triangulated have joints that must be rigidly fixed to keep from collapsing. These joints generate torque and bending moments and have high-energy requirements. Triangles are stable with flexible joints and have no torque or bending moments at the joints (Fig. 15.7). There are only tension and compression members in a triangle, so triangulated structures are low energy consumers. Because of their load distribution and high strength-to-weight ratios, engineers use truss systems made from triangles for constructing buildings and bridges. Intimately related to the laws of triangulation are the laws of closest packing (Pearce 1978). In a planar arrangement of structures, the space and energy efficient configuration is hexagonal closest packing, as in a beehive (Fig. 15.8). The laws of closest packing are the laws that apply to foams, colloids, and emulsions – the stuff of which biologic tissues are made (Perkowitz 2000). Thompson (1965) and later Gordon (1978), used truss systems to model biologic structures. As trusses are stable only when their joints are flexible, it follows that, if a structure has flexible joints and is stable, it must be triangulated. The mortar that holds biologic structures together is but slime. Stuck together by surface tension at the cellular level and loosely jointed at the organism level, biologic organisms must be hierarchical, fully triangulated constructs. Levin (2002) has described the evolution of the spine and skeletal system, from the cell (Ingber 2000) to the organism, as a hierarchical truss system with every body part structurally interdependent. The finite element, the building block of biologic tissue, appears to be the icosahedron (Levin 1986). The icosahedron is a regular solid with 20 triangular faces and 30 edges. Twelve vertices are created where three edges meet. Pressure on any point transmits along the 30 edges, some under tension, others under compression. It is possible to transfer all compression away from the outer edges by connecting opposite vertices of the icosahedron by compression rods. These rods do not pass through the center of the icosahedron but are eccentric and oddly angled; they hold the opposite corners away from each other. The outer shell of 30 edges is now entirely under tension, and the compression rods float

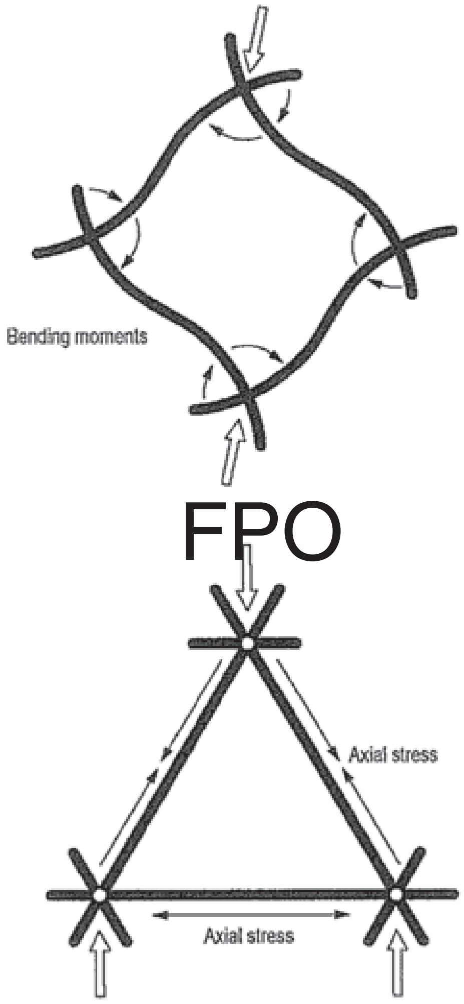

Fig. 15.7 Square frame structures are unstable and must have rigid joints to prevent collapse. Torque is created around these joints. Triangular frames are inherently stable, even with frictionless joints. The elements are under either tension or compression without any torque at the joints. (Adapted from Pearce 1978.)

Fig. 15.8 Hierarchical closest packing of circles to hexagons.

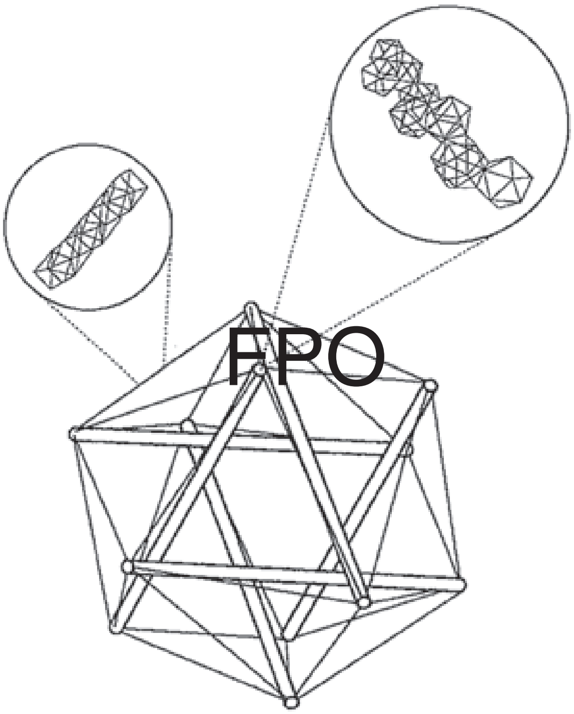

Fig. 15.9 A hierarchically constructed tensegrity icosahedron.

within this tension shell like an endoskeleton (Fig. 15.9). A load applied to this structure causes a uniform increase in tension around all the edges and this distributes compression loads evenly to the six compression members. The mechanical properties of a tensegrity icosahedron are that they are omnidirectional structures, with the compression members and tension elements always maintaining their respective properties regardless of the direction of applied load, just as the wire spokes of a bicycle wheel are always under tension and the hub is always being compressed. They can exist independent of gravity and are local load distributing. They have a unique structural property of behaving nonlinearly, as does the spine and its components, and most biologic tissue (Gordon 1988).

Fuller (1975) has shown that tensegrity icosahedra can link in an infinite array with any external form, as shown in Fig. 15.10. When linked, these structures can function as a single icosahedron in a hierarchical system. This model has been used to model endoskeletal structures, such as an upper extremity and spine (Levin 1990, 1997, 2002, 2005) with the bones functioning as the compression rods and the soft tissues as the tension elements. The concept that the musculoskeletal system is a continuous tension system is fully supported by Huijing et al's work on muscles and fascia (Huijing 1999, Huijing & Baan 2001a, 2001b), which has demonstrated that muscle is, in reality, one big organ functioning as a unit and all fascia is interconnected. This means that there would be no local loading of ligaments but that a load anywhere in the body is distributed throughout the fascial system. The structural model is represented by *The Needle*, a 20-meter tall tensegrity tower by Kenneth Snelson that sits in front of the Hirshhorn Museum in Washington, DC (Fig. 15.11).

If we apply these evolutionary structural concepts to the sacrum, we can see how the tensegrity sacropelvic model develops. The sacrum, fixed in space by the tension of its ligaments and fascial envelope, functions as the connecting link between the spine and

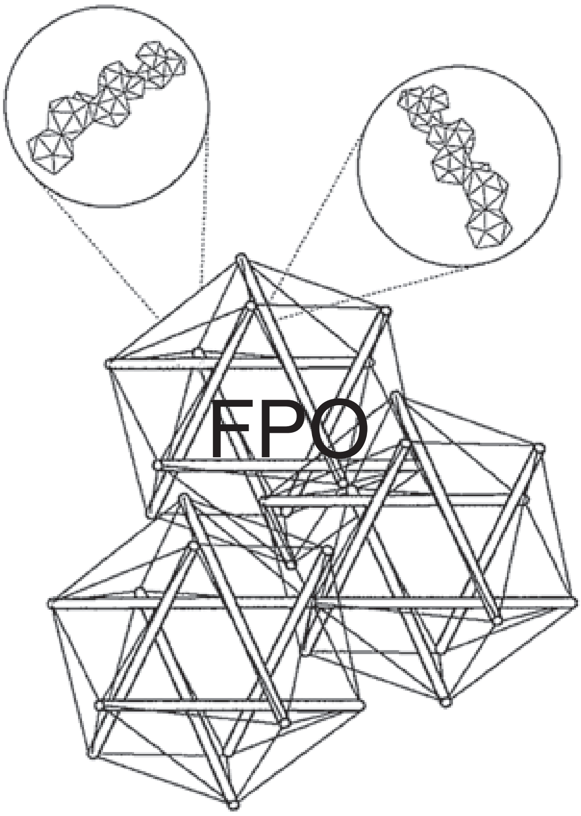

Fig. 15.10 An infinite array of tensegrity icosahedra. (Adapted from Fuller 1975.)

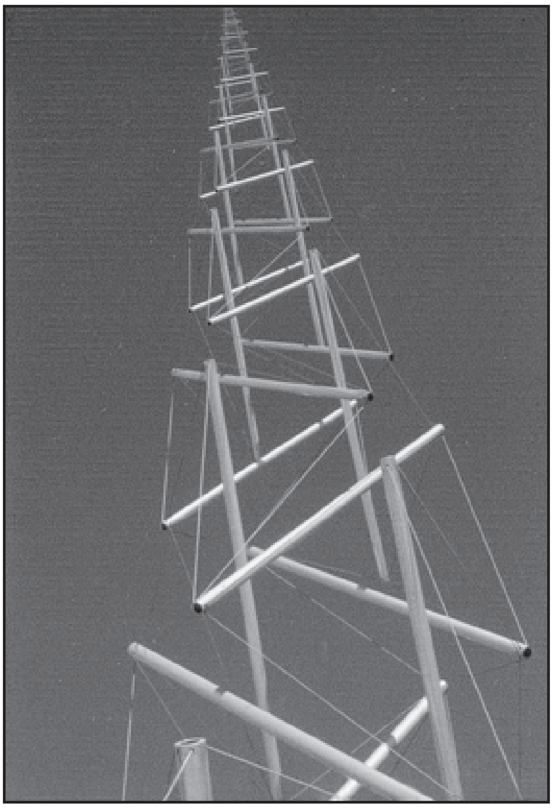

Fig. 15.11 *The Needle*. A 20-meter tall tensegrity tower. Hirshhorn Museum, Washington, DC.

upper (or forequarter) extremities, and the pelvis and lower (hindquarter) extremities. It evolved ontogenetically, directed not only by phylogenetic forces, but also by the physical forces of embryologic development (Thompson 1965, Wolff 1892). Carter (1991) theorizes that the mechanical forces *in utero* are the determinants of embryologic structure that, in turn, evolves to fetal and then newborn structure. From the physicalist and biomechanics viewpoint, as well as from Darwinian theory, the evolution of structure is an optimization problem (Fox 1988, Hildebrandt & Tromba 1984). 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. Ingber and colleagues (Ingber & Jamieson 1985, Wang et al 1993) have shown that the internal microtubular skeletal structure of a cell is a tensegrity icosahedron. Other subcellular structures, such as viruses, cletherins, and endocysts, are icosahedra (de Duve 1984, Wildy & Home 1963). 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 so is the bee's eye. Many other organelles and organisms look like and/or function as icosahedra (Levin 1982, 1986, 1990).

Following the concepts of Carter (1991), Wolff (1892), and Thompson (1965), a tensegrity-structured pelvis will build itself. Because the fetus develops upside down in a gravity-independent environment (like fish eggs in water), the pelvis develops as a tensegrity ring, which is the most efficient structure to do that job. It does not develop as a structure to resist superincumbent weight bearing. If it did, it would not function during its initial role in life of resisting *in utero* forces. The infant's pelvis would crush during delivery and the mother's pelvis would explode. A pelvis structured solely to bear weight on two legs would not serve the infant, (nor the adult,) well as it crawled on all fours. Ontogeny recapitulates phylogeny. The one-celled organism evolves as a series of stepwise mechanical accidents – which are consistent with physical laws and are the most energy efficient and most adaptable – into a complex, energy-efficient, symbiotic, multicelled organism. The different phyla get off the evolutionary ladder at different steps in the evolving process. To believe otherwise is to be a 'creationist' rather than a believer in Darwinian evolution. The development of a pelvis is not a 'design' but an evolutionary accident that worked in creating an energy-efficient, ambulating creature that could survive better in a gravity environment on land and could take advantage of the already evolved lungs that allowed breathing beyond the confines of the sea. It is the marvel of tensegrity structures that they are remarkably adaptable and can resist loads in a gravity-oriented environment equally well as they do when not affected by gravity (perhaps adding a few more trabeculae and ossifying some cartilage in accordance to Wolff's law). The pelvis is cancellous bone because the distributed loads require nothing more, nothing less. The ligaments are as strong as they need be to do what is required of them. Evolved to resist crushing forces from any direction, or exploding forces from within, the pelvis can adapt to unidirectional forces that are applied at two, three, or more points and distribute the load through the tension network of soft tissues that include local pelvic ligaments and extends throughout the entire fascial system (Huijing 1999, Huijing & Baan 2001a, 2001b) and compression network of bones.

Icosahedral tensegrity structures are self-organizing space frames that are hierarchical and evolutionary (Kroto 1988). They will build themselves, conforming to the laws of triangulation, closest packing, and, in biologic constructs, Wolff's Law. The pelvic wheel is a self-organizing structure that is part of a larger, fractal, space-frame, tensegrity construct with each part integrated into the whole. Simplicity and complexity intertwine in what Pearce (1978) calls 'minimum inventory, maximum diversity'.

Summary

Biologic structures, from subcellular to organism, are not constructed from rigid solids but from 'soft matter:' foams, colloids, and emulsions. The mechanics of soft matter differs from rigid solids in several ways (Perkowitz 2000). In biologic constructs, what has evolved, under the mechanical laws that apply to foam, is a system based on the tensegrity icosahedron, biotensegrity. This alternative approach to pelvic mechanics considers the pelvis part to be an integrated mechanical system based on the tensegrity icosahedron as its finite element. The sacrum is suspended in the interstices of the ligamentous structure like the hub of a wire bicycle wheel is suspended in the spokes. The ilia become part of the suspending 'rim.' This system can be used to model a static one-legged or two-legged stance, or the dynamic mechanical functions of the pelvis. Because of its ability to withstand omni directional forces, the tensegrity icosahedron is appropriate for modeling pelvic mechanics, from weight bearing to childbearing. Tensegrity structures are low-energy-requiring structures and, as such, are favored by natural selection. Because they are so adaptable and energy efficient, biotensegrity mechanics are also appropriate for modeling all biologic systems and sub-systems at each stage of their development and whatever their eventual function.

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