biotensegrity
a new way of modeling biologic forms

Putting the Shoulder to the Wheel:
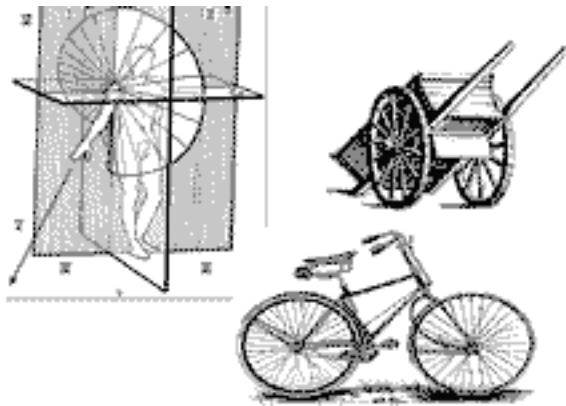# A New Biomechanical Model for the Shoulder Girdle

Figure 1.

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KEYWORDS

Shoulder, Biomechanics, Models, Tensegrity, Icosahedron, Fuller

ABSTRACT

The least successfully modeled joint complex has been the shoulder. In multi-segmented mathematical shoulder models rigid beams (the bones) act as a series of columns or levers to transmit forces or loads to the axial skeleton. Forces passing through the almost frictionless joints must, somehow, always be directed perfectly perpendicular to the joints as only loads directed at right angles to the surfaces could transfer across frictionless joints. Loads transmitted to the axial skeleton would have to pass through the moving ribs or the weak jointed clavicle and then through the ribs. A new model of the shoulder girdle, based on the tension icosahedron described by Buckminster Fuller, is proposed that permits the compression loads passing through the arm and shoulder to be transferred to the axial skeleton through its soft tissues. In this model the scapula "floats" in the tension network of shoulder girdle muscles just as the hub of the wire wheel is suspended in its tension network of spokes. With this construct inefficient beams

and levers are eliminated. A more energy efficient, load distributing, integrated, hierarchical system is created.

DISCUSSION

Figure 1. Shoulder abduction - adduction.

Loading a wagon wheel

Figure 2. Wagon wheel.

As the arm circumducts in any plane it inscribes the rim of an imaginary wheel (fig. 1). The arm becomes the spoke that transfers the load at the hand to the axial skeleton. Present models conceptualize the upper extremity as a wagon wheel spoke. In a wagon wheel model loads are transferred by connected rigid compressive columns or beams, the spokes, either by columnar loading or a crank-like lever transfer of loads (fig. 2). This is a classic Newtonian construction with columns, beams, levers and fulcrums with resulting bending moments and torque . The bones of the arm are envisioned as the rigid spokes but although there is a bony articulation at the glenohumeral joint that might be able to transfer compressive loads from the arm to the scapula there is no rigid, compressive load bearing structure between the scapula and the axial skeleton, nor is there a suitable fulcrum. In a linked lever system a seamless continuum of compression elements are necessary. Bone must compress bone. The almost frictionless joints would require forces to be always directed at right angles to the joint. The scapula is not anatomically situated to transfer loads through the ribs to the spine. Even if it were, the ribs could not take these loads and act as levers to connect to the spine.
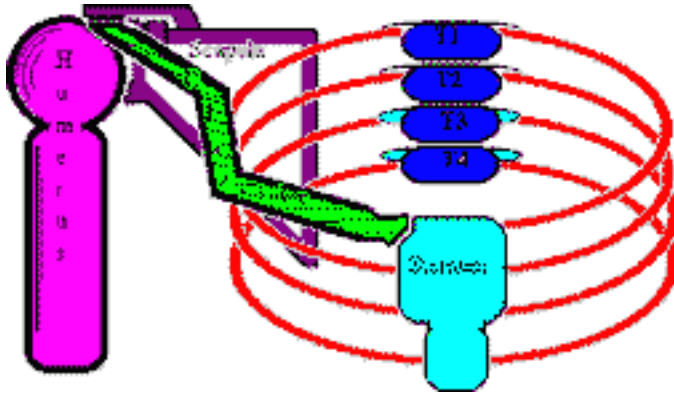
**Figure 3.** The shoulder "floats" on the chest wall.

The ribs themselves, by shape, position and connection, are not structurally capable of transferring these loads. The clavicle Is in no shape to transfer loads, either. It is a crank shaped beam that connects the scapula to the sternum by a small, mobile joint that could not transfer compressive loads of any significant magnitude (fig. 3). Cats do not have articulating clavicles and they can run and climb with the best of us creatures. The scapula hangs on the thorax by a network of muscles and all the moment and compression forces generated in the arm must be transferred to the axial skeleton through these soft tissues (fig. 4). A rope cannot withstand compressive loads nor can it function as a lever and neither can muscle. A wagon wheel which depends on rigid, compressive load bearing spokes to transfer loads and is not a suitable There is another wheel model which may be more appropriate. A wire cycle wheel transfers the compression (or tension) load at the rim and, through the spokes which are in tension, to the hub and then to the frame. Mechanically it behaves as a "Non- Newtonian" structure. The hub "floats" in a tension network of spokes. There are no bending moments or torque in a wire wheel. The compression members, the rim and the hub, do not press on each other, there is no fulcrum or levers analogy for shoulder girdle mechanics.

Figure 4.

The loads are distributed through the structure with no concentration of forces as there are in levers. Unlike a lever, which requires a rigid beam, fulcrum and a stable base to support the fulcrum, a wire wheel is a self contained entity. The loads are distributed through the structure with no

concentration of forces as there are in levers (fig. 5). A lever cannot function floating in a in a gravity free environment, a wire wheel can. Hooked together like the front and rear wheels of a bicycle, wire wheels can interact in a kinetic chain and transfer loads one to another. Bicycle wheels and similar structures with compression elements floating in a continuous tension network have been termed "tensegrity" structures (for continuous tension discontinuous compression) by Fuller (1975). His geodesic domes are examples of spherical shaped tensegrity structures. Viruses, C60, radiolaria, cletherins and cells are some organic structures that are tensegrity structures (Levin, 1990).
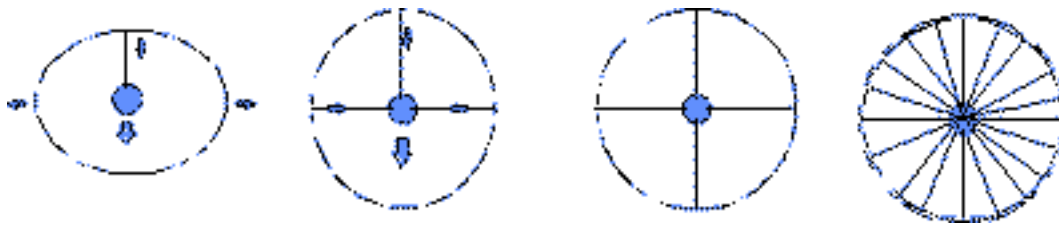
Figure 5. The hub of a wire wheel is suspended in a tension network. The axle load is hung from the top of the rim which tries to belly out. Additional tension spokes are added horizontally to resist the bulge. For circumferential stability the additional spokes are added. (After Fuller, 1975).

If we consider the scapula functioning as the hub of a tensegrity structure then the forces coming from the spoke-like arm could be transferred to the axial skeleton through the soft tissues rather than the circuitous and imposing linked levers of the bones. Muscles, as well as all other soft tissue elements in the body, are always under some tension. It is the tone of the muscle that holds us upright, keeps our jaw from dropping and our scapulas from sliding off our chest wall, as we do these things when the EMGs are electrically at rest (Basmajian, 1962). The tone of the muscles and the stored elastic energy in the soft tissues must be reckoned with to understand the forces that control stability and mobility in the body. The transfer of forces in the body could possibly be through these already tense soft tissue elements.

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

from a specific direction. Because the loads in tensegrity structure are distributed all the time each structural element can be lighter.

Grant (1952) used a tension model to suspend the body , hammock like, when it hangs between gymnastic parallel bars. However, hammock like suspension is unidirectional. Turn the hammock or suspension bridge over and, not only does everything fall out of the hammock or off the roadbed, the hammock or roadbed also collapses. A tensgrity structure can have one point of support coming from any direction, and still maintain its structural integrity. Like a truss beam cantilevered of a wall, the internal elements remain solely in tension or compression with no moments at the joints. When modeling a shoulder as a tensegrity structure the bones which "float" in the tension network of soft tissue are only being compressed. There are no moments at the joints because the structure is fully triangulated. In this model the shoulder becomes inherently stable and changes position only when one of the elements of the triangle is shortened or lengthened. Therefore, considerably less energy is needed to "stabilize" the joints.

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

The glenohumeral articulation may, at first, appear to be a more traditional compressive load bearing joint. But, for the joint to be stable forces must be directed at right angles (normal) to the joint. The glenohumeral joint is a multiaxial ball-and-socket joint with almost frictionless surfaces. The head of the humerus is larger than the glenoid fossa and the surfaces are incongruous ovals and not true spheres. There is no bony structural stability and the joint is loosely packed with a great deal of play between the surfaces. There are very few positions of the arm in which the humeral head directs its compressive forces normal to the glenoid fossa. Usually the forces are directed almost parallel to the joint surface. Since there is a change in direction of forces, in order to transfer forces to the scapula to glenohumeral joint must function much like the universal joint of an automobile drive shaft. As Fuller (1975) points out universal joints are analogous to the wire wheel as a basic tensegrity system. It relies a on the differentiation of tension and compression for its effectiveness. The soft tissues, the capsule, ligaments and muscles act as the connecting pins of a universal joint. Both the

scapulothoracic and the glenohumeral joints can be efficiently and easily modeled as tensegrity structured joints. As a rigid, multisegmented lever, modeling the shoulder is a struggle.
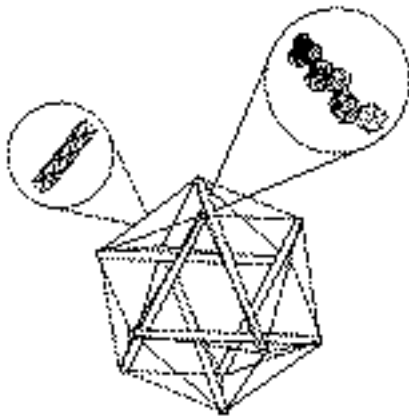
Figure 6. Tensegrity icosahedron.

Of the known tensegrity structures the tension icosahedron has particular attributes that make it the most suitable for biologic musculoskeletal modeling (Levin, 1986). Icosahedral tensegrity structures are self-organizing space frames that are hierarchical and evolutionary (Kroto, 1988) (fig. 6). They will build themselves, conforming to the laws of triangulation, close packing, and, in biologic constructs, Wolff?s law. The scapula, fixed in space by the tension of its muscles, ligaments and fascial envelope, functions as the connecting link between the spine and the upper arm, evolved ontogeneticaly directed not only by phylogenetic forces but also by the physical forces of embryologic development. Wolff (1892) and Thompson (1965) state that the structure of the body is essentially a blueprint of the forces applied to these structures. Carter (1991) theorizes that the mechanical forces in utero are the determinants of embryologic structure that, in turn, evolve to fetal and then newborn structure.
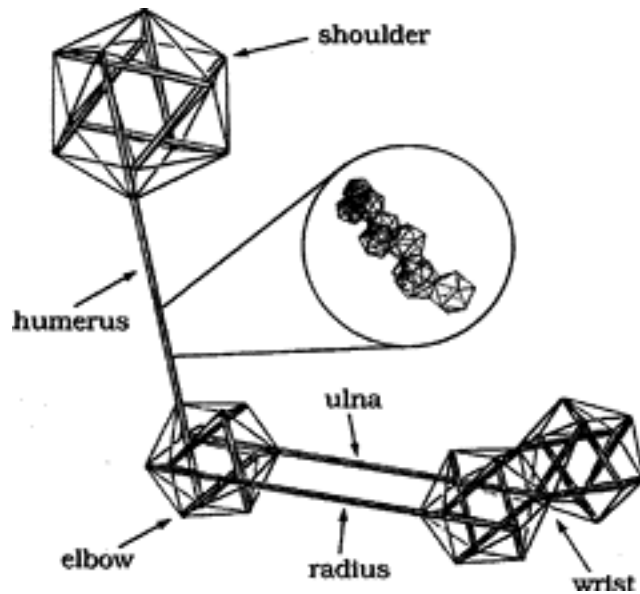
Figure 7. Tensegrity arm. Two levels of hierarchy.

From the physicalist and biomechanics viewpoint, as well as Darwinian theory, the evolution of structure is an optimization problem (Fox, 1988). 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 Jameson (1985) have shown that the internal microtubular skeletal structure of a cell is a tensegrity structure. 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. Following the concepts of Carter, Wolff and Thompson tensegrity structured shoulder will build itself (fig. 7).

CONCLUSION

This alternative approach to shoulder mechanics considers the shoulder part of an integrated mechanical system based on the tensegrity icosahedron as its finite element. This system can be used to model static or dynamic functions of the shoulder under compressive loads or tensile loads coming from any direction at any time. Because of its ability to withstand omnidirectional forces, the tensegrity icosahedron is appropriate for modeling shoulder mechanics for weight bearing, brachiating or swimming quadrupeds and flying birds equally well. Even more impressive is its ability to function in several of these modes in the same creature without any alteration of shape, strength, composition or mechanical function. Tensegrity structures are low energy requiring structures and, as such, are favored by natural selection. Since it is hierarchical and so adaptable, and energy efficient, icosahedral mechanics may also be appropriate for modeling all biologic systems and sub-systems at each stage of their development and whatever its eventual function.

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