Biotensegrity: the structural basis of life

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Biological structures are chaotic, non-linear, complex and unpredictable by their very nature …

(Levin, 2006, p. 79).

Key points: fundamental principles; haptic perception; morphogenesis; the future.

Biotensegrity is a structural design principle in biology that describes a relationship between all parts of an organism and the mechanical system that integrates them into a complete functional unit. It is a simple re-evaluation of anatomy as a network of structures under tension and others that are compressed – parts that pull things together and others that keep them apart – basic physics! Biotensegrity is also a *concept*, a *field of enquiry* that examines living forms through first principles and *it is not limited by a simple definition*.

Of course, at this point the reader may now be in somewhat of a quandary because this statement raises another paradox. Having defined the subject and then stated that it cannot be defined, an element of uncertainty has been introduced that either leads to some confusion or motivates further exploration to resolve the conundrum. Well, science is full of such paradoxes and trying to make sense of them is half the fun: pushing the boundaries to see what lies outside (and within).

In the simple model, every part contributes to stability of the whole structure and has a mechanical influence on all the others, with the closed-chain kinematics defining their interactions. The same principles also apply to living systems, but here the vast number of connections and variations in their mechanical properties can seem impossibly complicated and difficult to analyze using conventional methods. Biotensegrity naturally simplifies things because it considers just two elements – cables and struts – with the stick-and-string models demonstrating every aspect of their dynamics. Simple geometric shapes and the vector systems used to model the forces within them then help us to visualize anatomical structures as balanced energy networks and tangible displays of the invisible forces that hold them together (Levin, 2002). Complex morphogenesis begins with the atomic forces of attraction and repulsion and their spontaneous organization into simple and more complicated molecules, and its development always follows the same rules.

First principles

The Platonic shapes and where they lead to

The ancient Greeks considered that everything in the universe could be expressed through just five Platonic shapes – a view that persisted well into the nineteenth century – but this idea was overthrown when Charles Darwin published his groundbreaking book *On the Origin of Species* (Darwin, 1859; Ayala, 2007). Despite a brilliant effort by D'Arcy Thompson (1917) in relating biology to physics and geometry (Thompson, 1961), the driving force in developmental evolution came to be considered as little more than the random selection of clever artefactual contrivances, and these *just so happened* to meet the 'requirements' for improved biological function. The genetic code and Mendelian rules of heredity then seemed to seal the fate of Platonic geometry, but ironically, the discoverers of the DNA double helix had also reintroduced it back into biology.

In 1956, Francis Crick and James Watson suggested that the arrangement of proteins in the outer coating of the spherical viruses was likely to have cubic symmetry, just like the Platonic shapes, and this feature was subsequently confirmed in other molecular structures (Pauling, 1964). All spherical viruses are now known to conform to the icosahedral template (Figure 10.4); the cube and dodecahedron appear in some enzyme complexes; and certain cell membranes and photonic crystals (butterfly wing scales) develop around a cubic-cell gyroid. The helix, with its geometric origins rooted in the tetrahedron and icosahedron, is a common motif in proteins and cell walls; and even the functions of microtubules, collagen, and DNA are based on their quasicrystalline structures (Figure 6.6). Geometry as a major determinant of biological complexity in the subcellular realms has thus been reinstated (Denton et al., 2003; Van Anders et al., 2014)!

Of course, the development of more complicated systems is still going to be influenced by the same rules, and the whole of biology is an open display of these (Levin, 2002), but using conventional methods to follow the interplay between all the forces within them is near impossible. Which is why the simple stick-and-string models are so important: they demonstrate that the same principles that apply at the smallest scale also underpin the largest (and everything in between) *no matter how complicated the structure becomes.*

Simple geometry

The Platonic shapes demonstrated the organizing principles of geodesic geometry, close-packing and minimal-energy (Chapter 2), and the irrational Golden Mean that underpins all living systems (Figure 10.3). They introduced order and the concepts of emergence, modularity, heterarchy, and beginnings of complexity through the isotropic vector matrix. We have also seen how the tetrahelical template influences the nonlinear dynamics of more complicated tissues through crossed helical arrangements of collagen within blood vessels, the intervertebral disk, heart, myofascia, and entire body (Figure 6.9) where such heterarchical tubes maintain fluid flow and changes in shape without buckling or collapsing and are easily modeled through tensegrity (Figure 6.8).

As the high-frequency icosahedron approximates the efficient space-filling volume:surface area ratio of a sphere, so it combines with the T-icosa to model the flexible molecular surfaces of bubbles, viruses, the cytoskeleton and all natural spheres. The center of the T-icosa is essentially a stress-free zone that allows other things to happen within it (Figure 5.2). It is at the heart of the jitterbug and the minimal-energy configuration that compliant organic shapes will always try to assume (the ‘strange attractor’ of natural systems) (Huang et al., 2006; Levin, 2006). Biology is thus more about the physics of bubbles, foams and soft matter than some of the notions suggested by classical theory (Kapandji, 2012; Hirst, 2013) (Figure 12.1).

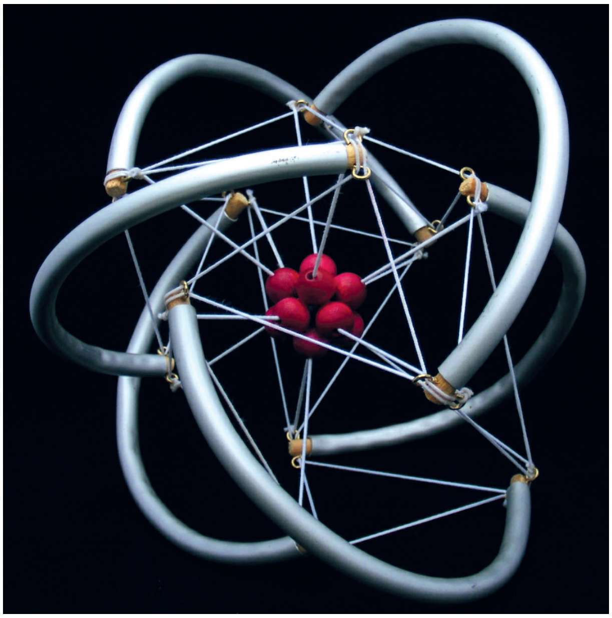

Figure 12.1
Model showing a relationship between the icosahedron and a curved-strut tensegrity.

The T-icosa serves to model the cranial vault and synovial joints, and as a modular chain, demonstrates how the spine can function much the same in any position and the head of a long-necked animal can be supported so far from its body, etc. Biotensegrity naturally leads geometry into the realm of biomechanics through its integrating CKCs and is the natural platform from which to better understand movement (Levin et al., 2017). It pervades the microphysiology of molecules, cells, the extracellular matrix and fascia, and is advancing research into their pathologies and treatment (Fiorino et al, 2014; Ingber et al., 2014; Tadeo et al, 2014).

The technology

Biotensegrity has also attracted the attention of engineers who devise novel ways to construct robots (Caluwaerts et al., 2014; Liu et al., 2017) that walk (Rieffel et al., 2010; Orki et al., 2012), swim (Moored et al., 2011), and bounce (Figure 12.2).

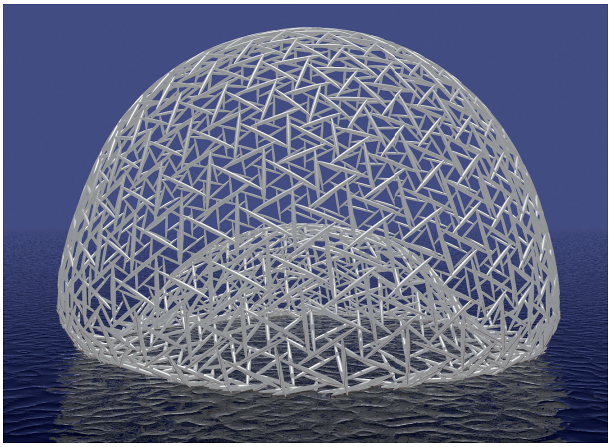

Figure 12.2
A computer model displays the organic-like deformation that occurs when a high-frequency tensegrity 'sphere' (6F T-icosa) is dropped onto a surface. (Reproduced from a video sequence courtesy of © Gerald de Jong (2010))

This is particularly useful in space exploration where the combination of strength, lightness, and flexibility are of paramount importance (SunSpiral et al., 2013; Mirletz et al., 2014; Rimoli, 2016). The 'Super Ball Bot' stands out because it is essentially a collapsible six-strut T-icosa that will automatically unfold itself as it lands before walking or rolling across some planetary landscape. It does so by continually adjusting the cable lengths and changing its center of mass (Figure 12.3), which is particularly interesting from our perspective because it uses the most basic of models to produce a structure that behaves in a very organic-like way. Such research has opened avenues that are likely to lead to new understandings of neurological control, and completely new classes of artificial joints and prostheses with both robotic and medical applications (Lessard et al., 2016).

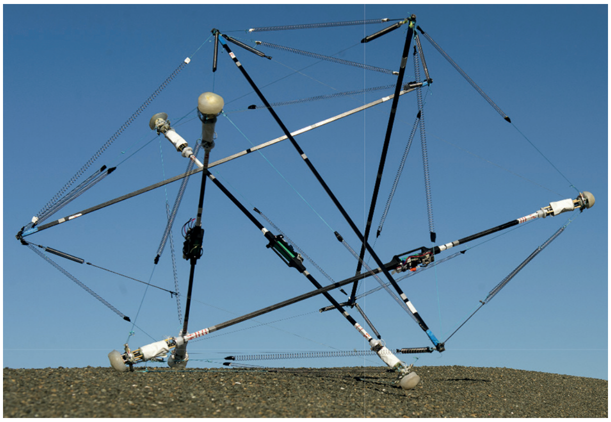

Figure 12.3
A prototype of NASA's 'Super Ball Bot' (T-icosa) built by Ken Caluwaerts of Ghent University. (Reproduced courtesy of Vytas SunSpiral and NASA Ames/Eric James (see Figure sources and permissions))

The unseen core

The use of simple models to examine the function of a particular anatomical region has been the mainstay of biomechanics for centuries but until recently there has been no clear principle that could unite them all (Figure 7.1). A tensegrity view of biomechanics is a model that sweeps away the man-made constraints of classical mechanics and presents a new way to understand living forms. It shows how multiple heterarchical levels can be integrated into compliant and flexible structures that are highly resilient to the effects of external forces. Where the continuous tension network is balanced by the elements of discontinuous compression within it, and the separation of these forces enables each 'component' part to become optimized to the loads that it carries, which makes them both light in weight and materially very efficient. A tensegrity configuration automatically balances itself, creates a highly-efficient control strategy that is built into the structure itself and contributes to dynamic stability. The potential of biotensegrity in exploring living systems thus seems to be limitless.

The emergence of form

Whenever nature uses the same principle in a variety of different situations there is probably an underlying energetic advantage to its appearance, and embryonic development and evolution will always lead to arrangements that are the most efficient in terms of stability, materials and mass (Serrao et al., 2017). Spatial organization and 'design,' however, are *not* written into some genetic 'blueprint' (or anywhere else) but result from a vast number of interactions between different molecules, cells, tissues, and complicated multifactor feedback pathways (Dinicola et al., 2011; Saetzler et al., 2011; Noble, 2017). Even though the genetic code plays an important role in determining an organism's particular characteristics, it can only do so if the basic elements of its structure are *already* in place, and the question as to *why* biology develops in the ways that it does still remains. What really are those fundamental principles that account for our observations of life and evolution?

The laws

All systems conform to certain basic principles, or 'rules of physics,' and the laws that we use to describe them are concise statements that summarize observations that are always the same. If the same thing happens over and over again, there is probably an underlying principle that causes it to behave in that way, and someone will then write a law about it. The laws, however, are *not the same* as the principles but our best understanding of them. They become established by consensus and are open to revision, and there are lots of them (Dhar & Giuliani, 2010). The laws of thermodynamics, for example, were formulated in the nineteenth century and are now considered to apply to everything, everywhere in the universe. They describe fundamental physical principles that are true, absolute, and unchanging (Ebeling, 2005). The First Law states that energy cannot be created or destroyed but only changed from one form to another – the conservation of energy. The Second Law indicates the direction that it always takes – from high to low – *toward* some minimal-energy state, yet it can seem at odds with biology. Both these laws apply to systems that are in equilibrium (or close to) where the energy dissipates and becomes equally distributed, while living organisms are characterized by order and complexity. Their dynamics are in a constant state of flux and exist in states that are *far* from equilibrium (Tan et al., 2016). There is also a Third Law but this only applies to systems with temperatures close to absolute zero, so we will leave this one aside.

Entropy

Coupled with this dissipation of energy is the concept of increasing entropy – an index of energy dispersal within and between a system and its surroundings – but it has nothing to do with disorder (Lambert, 2002). The Platonic shapes naturally appear in mineral crystals because of those basic principles of self-organization (Chapter 2) and which form minimal-energy structures that are relatively fixed and rigid, while the atoms within liquid and gaseous fluids are much less constrained; and biology is different again.

Living organisms are constantly taking in, storing and releasing energy to the environment – as nutrients, heat, waste, forces, and information – and the continuous dispersal of these resources *toward* some minimal-energy state naturally increases the entropy as part of the system's overwhelming drive *toward* equilibrium (Snir & Kamien, 2005; Van Anders et al., 2014; Frenkel, 2015). Entropy is really a measure of the number of degrees of freedom, microstates or 'possibilities' within the system, and a self-organizing processing system that increases it is an extremely efficient way of sustaining life's processes in a state of nonequilibrium (Fritzsche, 2017). Even though anatomical structures might appear to be stable and fixed, they are all just transitory states with an internal organization that is constantly changing from one moment to another (Teichtahl et al., 2015). The manner in which these resources are distributed is thus highly important because their flow through the system is what ultimately provides the power, and the architecture of that flow is constantly changing (see Foreword, p.xiii).

The architecture of flow

Power drives everything that moves, lives and flows, and the natural engines that produce it depend on the continuous flow of energy in, through and out of the system. One of the characteristics of life is the ability to transform its architecture in ways that enable these resources to flow more easily, and this is now summarized as the Constructal Law. Specifically: 'for a finite-size flow system to persist in time (to live) it must be able to evolve freely such that it provides greater access to its currents' (Bejan & Lorente, 2013; Bejan, 2016).[1]

It is an inherent tendency of natural flow systems to morph into configurations that facilitate access to what flows through them, and the branching patterns of rivers, dendrites, trees, arteries, and respiratory airways are easy examples

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[1] It is often suggested that the Constructal Law should be considered as the Fourth Law of thermodynamics because it explains things more completely.

(Reis & Miguel, 2004; Ball, 2016) (Figure 3.9). They are architectural solutions to increasing flow within a constantly evolving system, with the particular patterns forming in response to the driving currents and local constraints in the environments through which they flow. Each one is a continuous, one-way process in time where the dissipating flow channels automatically follow the path of least resistance and become established within an environment that may itself be changing.

Such a morphing flow system applies to every aspect of a developing and self-sustaining organism: from molecules that diffuse through a fluid environment and interact with each other in complex ways (Ball, 2015; Rutkowski & Swartz, 2007) to the flow of fluids through various tubular systems (e.g., vascular), and structural entities that carry the forces of tension and compression (Blechschmidt, 2004; Beloussov, 2008). Where the largest, stiffest structures transmit the greatest forces and distribute them to all the others, and the smallest ones 'collect' the little forces and transfer them up through the heterarchy to the larger structures. What we call cables, struts, and kinematic bars are then the geometric representations of a body-wide, anatomical morphing system that readily adapts its architectures to the forces that flow through it (Wolff's and Davis's laws) and is coupled to the cells that produce, maintain, and remodel it (Scarr, 2018).

The morphogenetic field

The spatial environments surrounding all these different flow architectures are then just as important as what passes through them. Each one contains its own distinctive flow systems that carry the currents toward their own minimal-energy 'sinks,' and feed into each other in complex ways, thus powering the overall dynamism that we recognize as life (Huang et al., 2006; Dinicola et al, 2011).

Even though the emerging pathways often display repeating characteristics (sometimes referred to as 'fractalization') each part of their formation is unique and the result of a continuous process that is quite different to the discrete mathematical iteration of a true fractal. The resulting arrangements may *look* like collages of the same design but are really just incidental, opportunistic and irregular statistical probabilities balanced between order and chaos. In the same vein, it is important to note that these organizational processes are not directed by some goal-oriented end point and have nothing to do with efficiency, maximization, optimization or intelligence per se. Even though biological systems typically display these characteristics, they are just observational phenomena that emerge *out of the process* and are not, in themselves, motivating or driving the system (Bejan & Lorente, 2013).

The developing organism emerges from *within itself, at each moment in time*, and in response to the constantly evolving flow systems that power it – it is its own morphogenetic field (Levin, 2006; Van der Wal, 2012)! A self-referential system that spontaneously changes its architecture according to some basic principles and constraints within the system, and evolves in a way that sustains life, and which is now touching the essence of what biotensegrity is really about.

Biotensegrity

Sustainability of flow is an overriding factor in an organism's existence and dependent on the organization of its emerging architectures (Kurakin, 2009). A prerequisite to life that is constantly evolving and entwined with the transition from conceptus to adult and the last breath, and through ovum and sperm to the new embryo … Each part is a unique modular entity nested within its own (and the larger) spatiotemporal environment and characterized by what flows through it. A self-organizing, small-world ecosystem suffused with complex feedback loops that modulate it (Zhang & Zhang, 2009; Saetzler et al., 2011).

From a biotensegrity perspective, the structures that were once simply labeled as molecules, cells, tissues, bones, muscles, and fascia have now become modular flow systems that transfer tension and compressional forces in particular ways; and the cables, struts and bars describe how they do this. The many-to-one mapping of their closed-chain kinematics then shows how the anatomy can change in a self-regulating way that provides both operational (functional) continuity and morphological diversity (Appendix 5) – the logic of morphology (Rapoport, 2011; van der Wal, 2012; Levin et al., 2017).

The flow of information

The biotensegrity model shows how information about the system can be transferred from one place to another in a controlled way and challenges traditional ideas about motion even further. The flow of changing forces, of course, depends on the particular stress–strain–kinematic properties of their flow-architectures (stiffness or compliance, viscoelasticity etc.), but it is also concurrent with the distribution of information about the entire structural network.

The source of that information is deformation, or rather a change in shape or position of one part relative to another, and the basis for haptic perception: the ability of an individual to appreciate its place in the environment by processing information received from its sensors of touch and position (van der Wal, 2012; Turvey & Fonseca, 2014). These are mechanoreceptors located in tissues particularly associated with the skin, muscles, and joints, and their deformation in response to changes in the local environment initiates signals that pass through the afferent nervous system to the brain. However, while this has traditionally been compared to a telephone exchange receiving discrete information from a vast number of otherwise isolated inputs, the computational processing of this in a way that leads to a meaningful response is questionable – it would be too slow.

The cycle of flow

The organization of the mesokinetic system can resolve this because it deforms in specific ways that relate to its biotensegral (CKC) architecture, and this intrinsically contains information about the state of the *entire* system. It is the medium of haptic perception through which mechanical (and other) information flows, and a defining characteristic that contributes to its effectiveness as a global processing network, as was described in the cytoskeleton, extracellular matrix and synovial joints.

The afferent sensory signals transmit information about the system to the somatic sensory cortex, but a much greater number of descending efferent projections run from the cortex to the thalamus, brainstem and spinal cord and are able to modulate subcortical activity in a flexible and dynamic way (Schleip et al., 2014; Petrof et al., 2015). So, while this sensory information is specific to the layout of the body, its continuities and transformations, it changes its nature from a spatial description of forces in terms of geometry, time, and kinematics to one that can be expressed neurologically (and in a more picturesque way) as patterns, spectra, and flows respectively (Turvey & Fonseca, 2014).

Such a system offers a faster and more refined level of precision than a computational one, with the ascending (receptive) and descending (modulating) pathways creating a dynamic neuronal variant of the structural architecture that can then inform a motor response. The information is not just being processed by the brain but across the entire haptic perceptual network, of which the brain and mesokinetic system are contributory parts. Perception and action thus involve different flow systems that operate synergistically within the mesokinetic body, and which both *provide and respond* to that information according to their temporally changing architecture. They are two sides of the same coin, the Möbius band and Klein bottle (Figure 10.14) (Rapoport, 2011; Turvey & Fonseca, 2014).

The continuity

Such a coupled system can then develop harmonic oscillations of information transfer that become entrained through complex feedback pathways and regulate every aspect of life's processes and activities (Pienta & Coffey, 1991; Schleip et al., 2014); and the potential for producing resonant oscillatory waves is intrinsic to the tensegrity model (Bliss et al., 2012; Castro-Arenas et al., 2017). An animal may also be able to reset its haptic system after a period of sleep through the process of pandiculation: a synchronized stretching of the myofascial tension system that quickly restores normal operating parameters and returns the system to its usual state of responsiveness (Bertolucci, 2011).

So, while the dissection of life into its constituent parts *necessarily* destroys the spatial order, the global biotensegrity concept reveals the self-organized continuities that distinguish it from a soup of chemicals, and the emerging flow architectures that enable it to adapt to the ever-changing environment (Figure 12.4).

The functional organism

Modern anatomy has accumulated a body of knowledge that is unrivaled in any other sphere. It has classified structures according to the thinking of the day and sought to understand their functions with the latest technologies. As things have progressed, so the names and perceived functions have changed, with new aspects introduced, but these take time to be assimilated and the imagery

Figure 12.4
(A) Pandiculating tiger (*Panthera tigris altaica*) resetting its haptic perception system. (Reproduced from © Malene Thysson, Wikipedia). (B) A standing goose (*Branta canadensis*) stabilized by the geometry of its closed-chain kinematics. (C) A Flamenco dancer showing off her force-flow architecture. (Reproduced from © Tony Hisgett, Wikipedia)

associated with the old ones often persists. The outdated 'musculoskeletal' duality is one such entity that has now been replaced with a new name – the mesokinetic system – because it links bones, muscles, and connective tissues into a complete functional unit. The anatomy remains unchanged but our understanding of it is now different.

This book is about anatomy: the study of living form and structure; kinematics: the geometry of motion; and energetics: the flow of information, with biotensegrity providing the global continuity that unites them. It represents a paradigm shift in the way we think about biology because it is based on the fundamental rules of physics *first* and from which everything else is derived, and is thus quite different to the contrived methods that have dominated for centuries. Biotensegrity reveals the facts of life that we were never taught and gives new insights into the workings of the human body, and the application of such knowledge is bound to have far-reaching consequences. A dysfunctioning body still operates according to the same basic principles as a healthy one, but with a different set of constraints and flow architectures, and biotensegrity provides the rationale for the physician (of every flavor) to make changes that allow the dynamic body to shift toward an improved state of health.

Both simple molecules and complex structures result from the interactions of pure energy (forces), and although particular configurations dominate they are not especially chosen by nature but because their simplicity, efficiency, and stability favors them. An organism's survival depends on the integration of all its parts – from molecules to the entire mesokinetic system – and is an arrangement that has refined itself over hundreds of millions of years. The real beauty of nature is that it does so much with so little!

The journey has just begun …

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Thus, beyond all questions of quantity there lie questions of pattern, which are essential for the understanding of Nature.

(Alfred North Whitehead, 1934)