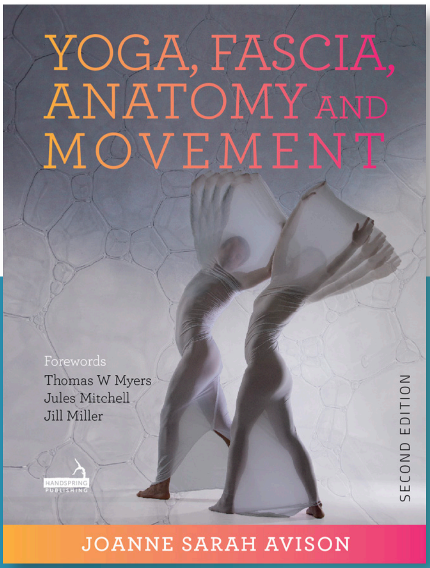

The Fascia Hub presentation of The Fascial Spine

November 6th 2021

Excerpt from YOGA FASCIA ANATOMY & MOVEMENT
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In this excerpt Joanne Avison explores the work of Serge Gracovetsky's SPINAL ENGINE.

Chapter 9, Curved is the New Straight will support and guide the practical applications of several aspects discussed and presented at The Fascial Spine event, with notes from the references of the full chapter.

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Curved is the New Straight

"The commonly accepted 'tower of blocks' model for vertebrate spine mechanics is only useful when modeling a perfectly balanced, upright, immobile spine. Using that model, in any other position than perfectly upright, the forces generated will tear muscle, crush bone and exhaust energy. A new model of the spine uses a tensegrity-truss system that will model the spine right side up, upside-down or in any position, static or dynamic. In a tensegrity-truss model, the loads distribute through the system only in tension or compression. As in all truss systems, there are no levers and no moments at the joints. The model behaves non-linearly and is energy efficient. Unlike a tower of blocks, it is independent of gravity and functions equally well on land, at sea, in the air or in space and models the spines of fish and fowl, bird and beast."[1]

Stephen Levin

As movement teachers we have to hit the ground running. People who sign up for a yoga class want you to join the dots at the speed they can move and understand the ways they can do it. They want those ways optimised, so what aspects of biomechanics do we need to learn in order to enhance and ensure this optimal practice? In the last chapter we considered that muscles do not, in fact, function as units, which changes how we might explain their role in any actions. There is still a difficult gap between classical biomechanical explanations of movement of our parts and the natural experience in the yoga classroom of how participants animate, in stillness or in sequences. Finding accurate distinctions is especially challenging when considering the fascial matrix as a tension–compression network under the biomotionally intelligent model of living tensegrity architectures. How can we bridge the difference between anatomy and architecture, classical and connected forms and "Cross the Rubicon",[2] from biomechanical to biomotional?

Moving Architecture

In standard biomechanics, the first thing a new student is invited to do is work from an imaginary axis, a central vertical line down the middle of the body that acts as a reference point for the planes: sagittal (lateral, median – *divides* *the body into left and right sides*), coronal (frontal – *divides the body into front and back*, or dorsal/ventral or anterior/posterior) and transverse (axial, horizontal – *divides the body into upper and lower* – superior/inferior, cranial/caudal). These planes separate movement into right/left and front/back and upper/lower (rotational motion) aspects, in order to describe human actions by reference to these planes and dimensions (Fig. 9.1).

However, we do not in reality have a straight line down the middle of us, and we do not move in straight lines or flat planes, nor does our body divide easily into symmetrical halves, in any dimension. We do not naturally stand in the anatomical position and our spines do not behave as vertical columns that have to be upright to function; let's agree with da Vinci that the spine is curved. It is a useful method to describe planes of motion. However, it becomes painfully difficult to make sense of yoga in these terms, even on paper, let alone at the speed of a classroom full of self-contained whole bodies in asymmetrical volumes, moving in *any* and all directions.

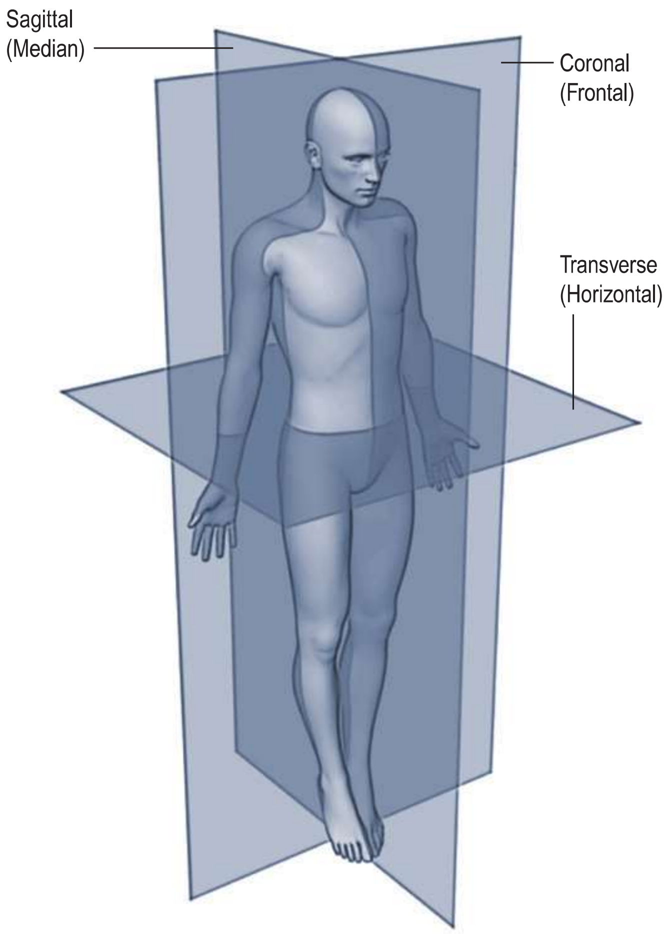

Figure 9.1

Body planes.

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It keeps us under the spell of the "straight spine". Does nature's propensity for working with roundnesses in volumes invite us to search for a more useful starting premise than this imaginary straight pole, divided into perfect quadrants on x, y and z axes? Ontogenetically (since conception), we challenge this from the relentlessly curved performances of the embryo. From an evolutionary viewpoint, there are more clues to suggest that curves are fundamental to healthy motion. According to Serge Gracovetsky, Stephen Levin, John Sharkey, Jaap van der Wal and others (see the notes and suggestions for further reading at the end of this chapter) it shapes our shape and fundamental movement patterns profoundly, which calls for explanations that make more sense of them. It is accepted as a language of convenience, if we remember that is *all it is*.

Contemporary Questions for Classical Assumptions

Into this inquisitive gap between the classical theories and contemporary interpretations walked Serge Gracovetsky PhD, to present at the first Fascia Research Congress in 2007, at Harvard Medical School, Boston, Massachusetts.[3,4]

The Spine as an Engine; the Story Behind a New View

Gracovetsky emphasises that the human form is entirely designed for agility, not for rigidity (as if the spine was stacked, as denoted by the term "column"). His spinal engine theory (see also notes and further reading) is like water in the overheated arguments of a dry biomechanical desert. It is complex; however, it breaks many spells by showing logically how the whole spine moves in all its various segments and natural curvatures. It is dependent upon the intimate relationships between muscles and the collagen matrix in which they reside, to transmit forces (between the head and the earth, via the rotation of the shoulder girdle and the counter-rotation of the pelvic girdle and through the feet), to and from the ground. That is, via the gears (locking facets) of the *essentially curved* and *essentially rotational capacity* of the human spine and its *appropriate* motions. He points at the complexity in the detail that is reduced to an axis, if we underestimate the spine's authority in motion.

According to Gracovetsky, when we bend forward or lift an object, for example, the spine naturally switches back and forth within fractions of a second between tension and inhibition (see Appendix B). That is the tensional strength of the collagen and the active contraction/inhibition of appropriate neuro-muscular responses. That is at specific frequencies for the load/interaction at the time. This is, effectively, a fast reaction between tension and compression forces, *through the motion* and *architecture* and *morphology* of the *curved* spine. Rotation and counter-rotation drive the spinal engine, based upon its *curved structural* design and "neuro-myo-osseo-fascial" (my phrase) organisation. It responds rapidly to tension/compression signals of motion through its myofascial–collagen network. Standard biomechanical suggestion that the torso is carried along by the legs as a sort of passenger, stacked upon the pelvis, is properly challenged (see further reading). Gracovetsky suggests that the spine comes first; the limbs come after as an *advantage* to energy management and conservation, *refining* our basic spinal movement signature rather than dominating or dissecting it. (Which is compelling, since it recapitulates our embryonic sequence of self-assembly – see Ch. 4.)

It is not a common event to see a standing ovation at a scientific research congress. Nevertheless, Gracovetsky made so much sense of what we experience in the real living spine, founded in fundamental laws of motion and the geometry of the collagen matrix, that the audience celebrated his candid and highly researched reasoning with cheers. He pointed out that because there was an assumption that movement was based upon the musculoskeletal system, measuring devices were developed over the centuries that based calculations almost exclusively on examining muscular action. This reinforced the musculoskeletal bias of classical anatomy and subsequent theories of function that largely ignore the integrated nature of the fascia. Thus, any living (in vivo) testing perpetuated the assumptions and allowed science to bypass the crucial role of the collagen matrix in movement; *it wasn't considered, let alone measured.* Traditionally, the fascia was overlooked both anatomically and biomechanically, at least in terms of its ubiquitous continuity – certainly in terms of its sensory signaling and force transmission roles. It was simply left out of most of the equations. That is turning out to be a crucial omission.

Recently, advances in equipment and methods of investigation, particularly more sensitive ultrasound and MRI devices,[5] have allowed the reading of fascial structures in vivo to endorse the essential role of collagen everywhere in the body, including the spine. Science has also begun to ask different questions, hence this paradigm shift and the advent of a whole new level of curiosity and enquiry. Biotensegrity features heavily in many of the emerging models, since it fundamentally explains volumes, round things and curvatures that are self-assembled into whole adaptable, shape-changing creatures.

> *"The wide range of human physical activities obscures the relative simplicity of the physics behind movement. From the moment the legendary fish emerged from the water and landed on solid ground, the development of anatomy was shaped by the need to conserve energy. In this context, the Earth's gravitational field became another natural resource that our species learned to exploit."*[6]

In the gravitational field on earth creatures move around as a constant management system (or physical interpretation) of ground reaction force.

> *"GRF simply means that the ground is pushing back to whatever is pushing down on it. (Newton's 3rd law, for every action there is an equal and opposite reaction; if you push on a wall the wall is pushing back equally.) If someone is walking or running, F=ma (Force = mass x acceleration; Newton's 2nd law), so the GRF would be greater."*[7]

Serge Gracovetsky explains it another useful way, to emphasise further how completely we rely on this force in all interactions on the earth: using the legs to translate the energy we store temporarily with every step. We take it so completely for granted, we are not even aware of it as a distinct balance of forces that account for our homeostasis; the self-containment of being here – standing or sitting on a mat – is already an achievement!!

> *"To understand the concept, first note that you are not in a free fall, even if your body is subjected to the earth's gravitational field. This happens because the ground under your feet opposes a force equal to the weight of your body and hence your feet are in equilibrium. If something happened to the ground (a sink hole that would open up) then your body would fall towards the center of the earth."*
>
> **Serge Gracovetsky**

The hummingbird, we learned, cannot maintain its ability to beat its wings at a rate of approximately 100 beats per second based on classical theories of muscular energy production. The mathematics (upon which biomechanics are generally calculated) of the energy required means the hummingbird would generate so much heat it would burst into flames. On a similar basis, Olympic weightlifters raising anything over 50 kg would routinely explode if they really were relying on "intra-abdominal pressure" as the basis of their power to lift, due to the forces involved, were they *really* to be relying on this functionally. Gracovetsky debunks what he calls the "myths and fairy tales of musculoskeletal anatomy". *He challenges the standard theories of biomechanical force transmission, based on levers moved by muscles at joints* that don't necessarily stand up to mathematical scrutiny, however long they have been believed.

Since the first edition of this book, I understand from Dr Stephen Levin that Gracovetsky espouses biotensegrity as a founding explanation for his theory.

Collagen, he explains, plays a "fundamental role" in spinning (elastic recoil – see Ch. 10) a hummingbird's wings, shaping and moving the spine, whether or not it has been understood or accurately accounted for. Importantly he emphasises natural spinal curvature, in upright posture as an asset of "*biomotional integration*" (my phrase). Gracovetsky walks us scientifically towards a fuller appreciation of *curved* motion mechanics (if they can be called that), challenging some basic, long-held classical assumptions.

The ground reaction forces are nothing more than the "equaliser forces" to gravity, keeping you in balance (*allostasis)* during your everyday life.

> *"When you walk, the ground must oppose a force to your foot (precisely and exactly equal to your mass) and that is what is called the 'heel strike pulse'."*
>
> **Serge Gracovetsky**

At the conference, the idea that "intra-abdominal pressure" sufficient to weight-lift 50 kg would cause the weightlifter to explode, was hilarious – and Gracovetsky has done the math! He wryly recommended that personal trainers make sure they get paid before their clients lift anything, just in case such classical myths are accurate!

When you sleep, your body shape is imprinted into the mattress because the mattress is soft and crumpled when the ground reaction forces push UP into your body.

In real terms, we animate different ways of expressing this relentless dependence on the mutual relationship between gravity and its counterforce (ground reaction force; GRF[8]). We can dance "lightly" or stamp "heavily" depending upon how we animate our tissues, moment to moment, so the experience of it can change – due to the *internal forces*. The GRF remains the same, but we can actively modify how the forces move *through* our connected tissues. We can tension and compress their connections elastically; using the ground (constantly), as a temporary energy store. We can move over it, as if it was a trampoline or a treadmill, using our own bodies as the elastic recoil mechanism (see Ch. 10, The Elastic Body).

If the ground is covered in snow or sand, as distinct from being a dense, hard, flat road for example, then the way in which our tissues respond changes accordingly. We then have to react and organise *internal forces* to account for that difference in "heel strike pulse" (i.e. energy return). Our experience then, might be less of a "bounce back" and we need to adapt and generate more (*myofascial effort* and *metabolic*) energy to move over that softer terrain, when its particles are not so dense or close packed: which means they don't *return* the energy of the heel strike pulse as rapidly or directly. *There is less resistance to deformation* (see Ch. 10). We naturally navigate this all the time, consciously or not. Your body *already* knows how to do this instinctively. It lives in a mutual balance between gravity's radial pull towards the centre of the earth and (any creature's) ability to occupy space in response *from* it, i.e. in direct response or reaction from the ground (thus the term *ground reaction force*).

Our bones (which Levin refers to as "starched fascia"[9,10]) are originally formed *as a result of* the day-to-day management of forces, of our reaction to the ground (and the balanced, mutual pull, or pressure, of gravity towards it). We exist as three-dimensional form in relationship to this force-and-counterforce balance. We are not crushed; we are able to stand up and move around, away from the ground. We don't float off it, either; we can spring off, however we are literally and symbolically *bound to return.*

We could say this innate ability is a unifying of triune forces. In a tension–compression system we have three elements: (1) tension, (2) compression and (3) combined tension–compression, which is a *whole* volumetric material, expressed in a certain pattern, as a certain organisation of tension and compression forces. (The way they are combined, i.e. the pattern, matters.) We also have three elements of gravity and ground reaction force: (1) gravity, (2) GRF, and (3) their combination, which shows up **as our structural integrity** – the result of their combined forces as our physical *expression* of wholeness. Your ability to move around as a living volume, is an expression of how you interpret gravity and ground reaction force through your physical structure at any one moment in time; in your body's own language at the time. Essentially, your ability to stand still, given that muscles only contract,[11,12] is an asset of a healthy nervous system that can *inhibit that contraction appropriately* at a given point in time and any given point in your myofascial home (aka your body architecture). Homeostasis, or allostasis, is not just about movement; it is the ability to stabilise at will, given our innate mobility and motility and the environment we move it around in (and the muscles' innate predisposition to contraction). It is dynamic balance, rather than default prejudice.

The ground interrupts the relentless pull towards the centre of the earth all the time. Our human ability to resist this pull affects and expresses the health of our whole system, so much so that we do not even have to think about it. We are already its consequences in space and time. We rely on these mutual forces for our structural integrity. We do this instinctively, whether or not we understand them intellectually.

From an evolutionary point of view, we have acquired the ability to manage ground reaction force (perhaps what Scaravelli[13] refers to, in yoga, as our "anti-gravity reflex") in ever more refined ways. Newton is credited with discovering the distinction of gravity but, according to Levin, there are different interpretations for the way that biologic soft architectures move, independently of that gravitational pull. It may be also a question of how literally we translate Newton's laws. An equal and opposite force is at work in living tensegrity structures (tension and compression) at all times. However, they resist deformation naturally in omnidirectional ways (in yet another equal and opposite system of force transmission, expressed as gravity and ground reaction force). Studies of how our tissues *really* respond to stress and strain suggest they do so in non-Hookean (i.e. non-linear) ways.

> *"This [tensegrity structural behaviour, measured in a stress-strain graph] is radically different from the Hookean, linear behavior of most non-biologic materials and structures. In Hookean structures for each increment of stress, there is a proportional strain until the point of elastic deformation, just before it breaks. Hookean structures weaken under load. In the tensegrity structures, there is rapid deformation with the initial load but then the structure [responds and] stiffens and becomes more rigid and stronger."*[14] *[n.b. it is self-regulating]*

Levin details how tensegrity structures explain our omnidirectional strength and ability to resist deformation. This challenges the "spring and dashpot" model as somewhat contrived and suggests something actually more direct for the way we explain structure, given how we naturally move and respond *as living tensegrity volumes*.

Evolutionary Movement Requirements

According to Gracovetsky, our spines originated (evolutionarily) in creatures that had to be able to move over slippery mud when they emerged from the sea and had to adapt accordingly, to evolve. The side-to-side (lateral) motion of fish was not so efficient over land (Figs 9.2A and 9.3B).

The forward and back motion (flexion and extension) had to develop from an evolutionary point of view, if the animal body was to move over rocky terrain and eventually find upright motion.

To do this, these two planes of motion gave rise to the helical motion potential (see Fig. 9.2B) that could exploit the gravitational field, rather than be defeated by it. This was rotation and counter-rotation between the shoulder and pelvic girdles (the key drivers of the spinal engine[15]). This occurred in concert with the developing appropriate curvature of the spine and the

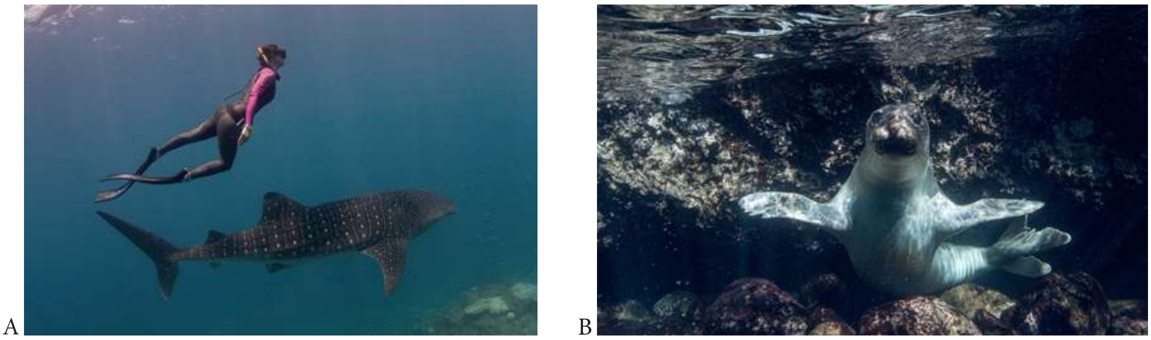

Figure 9.2AB

(A) Human motion. This freediver (Michèle Monico) naturally moves in a human motion pattern (flexion extension based) compared to a shark, which relies on a lateral motion pattern. (B) Here the elephant seal shows exactly how the “Law of Coupled Motion” works: extension and lateral flexion, giving rise to rotation.

Photographs by William Winram © Freediver Michèle Monico *blessed with the company of a beautiful Whale shark (Rhincodon typus)*
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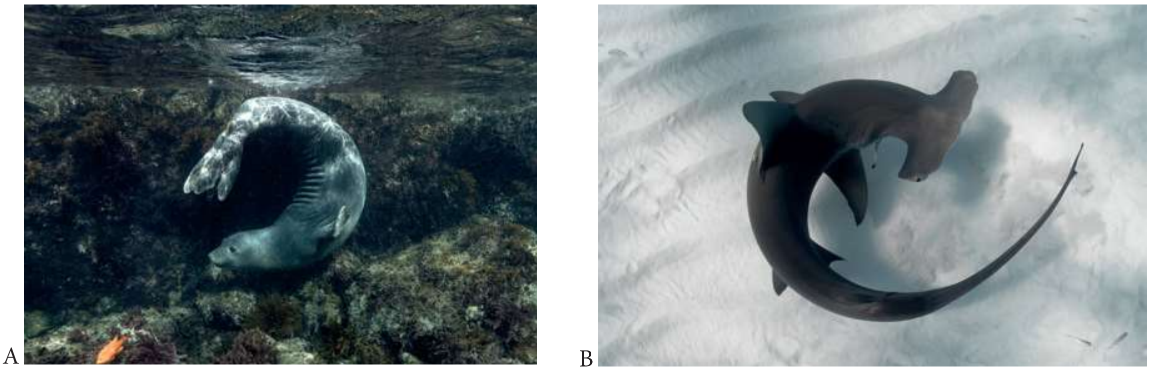

Figure 9.3AB

This elephant seal (A) can arch its back in a mammalian full extension pattern, whereas the hammerhead shark (B) relies upon only lateral flexion for its movement range, to propel itself forward.

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evolutionary development of the limbs and extremities on land. The evolving gait patterns produced an integrated whole-body movement capacity greater than a contrived lever-based mechanism that fits the sum of the parts together (as in building Pinocchio).

Spine First

"Locomotion was first achieved by the motion of the spine. The legs came after as an improvement, not as a substitute."[10]

Many theories of upright two-legged (bipedal) human movement suggest the legs authorise or initiate gait and the torso, or axial body, "travels along as a passenger" (to quote Gracovetsky). As he points out, from an evolutionary point of view (that recapitulates the embryonic forming sequence), the legs developed as an asset for living on land. Lower limbs are among the later structures to grow, some embryological time after the spinal structures are in place and after the arms (upper limbs).

Gracovetsky debunks the theory that the lower limbs drive gait by asking what happens if there are none. Would that mean the spine does not work (or "walk")? He filmed and monitored (with sensors along the spine) a man without *any* limbs, who could nevertheless move along the ground in a natural walking gait-pattern. Gracovetsky analysed the torso movements, which match those of a person with legs to walk on and arms to swing. Any theory of walking that presumes initiation in the legs is challenged by this research. (In close-up video footage of the spine it was impossible to detect that the person walking had no arms or legs and in fact walked directly on their sitting bones (ischial tuberosities), rotating and counter-rotating the torso to move over the ground.)

Gracovetsky shows that in human walking, the lumbar curve of the spine is paramount in the translation of forces to and from the ground, via the legs. Rather than a passive passenger, carried along by them, it is the *author* of gait. According to Gracovetsky, the spine drives the limbs from above, which allows the legs to translate the *amplitude* and *quality*, or *resonance* of the movement forces to and from the ground using it step by step as a temporary energy store (via the heel strike pulse). As yoga teachers, we are well served by understanding this organisation and Gracovetsky provides cogent reasons why it is an advantage to keep the body supple and mobile, to naturally translate energy as efficiently as possible (his work is referenced throughout the notes and in the further reading suggestions at the end of this chapter).[16]

The spinal engine theory is in fact congruent with Levin's tensegrity-truss model and Flemons' tensegrity models (see Ch. 10, Fig. 10.6); if you remember, they are modeling force transmission, not body parts. As closed kinematic chain[17] models, they naturally evoke the law of coupled motion (see later in this chapter). It begins to make sense of our ability in the yoga classroom to balance on hands and head, shoulders and elbows at various angles of poise in all but flat planes and the anatomical position. The spine becomes the common denominator: rotation and counter-rotation work both ways up. We could say that lying in Corpse Pose (Shivasana) resembles the anatomical position. However, even then, we can use that pose to experience and sense our natural curvature on the ground, using it for feedback directly (see Ch. 11 for a specific exercise). We do not experience ourselves as flat to the mat; nor would we want to.

This exercise makes sense of Gracovetsky's view suggesting that the spine acts, albeit upright, in the same way as the spine in any sea mammal, with the limbs adding balance and ballast and further facility, rather than necessarily driving or originating the movement pattern (although they can orchestrate movements in a seamless integration). A bird's spine also has to navigate the different forces transmitted through flying and walking; once again, we discover that biotensegrity offers a model that binds on land or in the air or sea.

"Lordosis [lumbar curve] emerges as the single most important parameter in controlling the force transmission between the legs and the upper extremities."[18]

Gracovetsky shows that the limbs help to translate forces, driven by the spine, to and from the ground, refining them to the most appropriate amplitude, or shape, for the spine to receive and respond energetically, to the forces transmitted through it.

Exercise: Sitting in Staff Pose (Dandasana), it is possible to fold the arms, slightly bend and stiffen the legs and "walk" up and down the mat on the sitting bones, sliding the legs along the mat (bend the knees and lightly place the heels on the mat). It reveals the natural rotational reflex through the spine to make these motions. After "walking" up and down the mat on sitting bones, try it on the knees and then in standing with the additional "lift" of the legs. It seems to immediately facilitate a lightness of step and quality of elastic momentum. There is a change in amplitude but not in the fundamental ability to make the movements. It can be experienced as the same rotational pattern at different frequencies through the body, depending upon how close the spine is to the ground.

Primary and Secondary Curves

The curves of the spine (Fig. 9.4 and seen in Fig 9.2A) can be considered, as has been pointed out, from both an evolutionary (*phylogenetic*) and a developmental (*ontogenetic*) point of view. The reason the spinal curves are named primary and secondary is that the primary curves are formed before we are born (in utero) and the secondary curves develop over time, later (ex utero), through movement patterns and their force transmission, becoming a pattern in the soft tissues.[19]

One or Two Legs?

Levin goes further to suggest we are designed for *unipedal*, rather than *bipedal* posture. Once we learn to stand on two legs, we frequently use them one at a time. Indeed, in walking we spend up to 80% of our movement on one leg and in sprinting, the body travels through the air and is invariably on only one leg or the other. We even tend to favour standing on one leg rather than two. (Ask your students which is their favourite standing leg – most people prefer one as a default pattern.) We can certainly afford to explore this idea with some enthusiasm, given the most basic list of yogic asanas that develop exactly that aspect of balance and physical literacy, training us to do postures to each side and bring the same level of ability and agility and balance to both.

Animating our Curves in Three Dimensions

Gracovetsky shows that various laws of movement are animated by the fundamental design of a curved spine. His research makes sense of our yoga practice by acknowledging whole spinal performance. In walking, running, dancing and even sitting, we actually use the whole body, as we breathe. Gracovetsky emphasises the value of a curved/counter-curved central axis, rather than the primary curve structure such as our primate cousins embody. He embellishes the purpose of the primary and secondary curves. We have the natural ability to rotate, counter-rotate, side, forward and back bend. (We can do a lot more besides, incorporating subtle movements and spirals, in between these main classifications that are not so easy to label in classical biomechanical terminology; see Ch. 18.) The spinal engine theory clearly makes sense of the natural design of our structural relationships to the ground. We will explore this through practice in Part C (Chapters 14 & 15).

Very soon after birth, the forward-folded form of the curled ball (primary curve) of a healthy newborn (neonate) will attempt to lift its relatively large and heavy head (pressing down on mother's shoulder to push up, for example) and naturally begin to activate (through instinctive usage patterns) a curve at the neck (extension). This is the first of the two secondary curves of the spinal "S", crucial to our ability to spring and to the spine's ability to rotate and counter-rotate once we begin to fulfil our soft-tissue, architectural promise.

Lumbar lordosis, the secondary curve at the back of the waist, is formed after the secondary curve at the neck. It is prescribed as the baby learns to push and lift up from the ground and to twist.

Animated by natural curiosity, a baby uses rotational movements and side bends, as well as forward bending and back bending, to roll over, lift its head (and eventually chest) off the surface it is resting on. It mimics the evolutionary patterns describing our emergence from the sea, perhaps unsurprisingly! Ultimately it strengthens its back enough to raise head and torso, curving the spine back (secondary) as well as forward (primary). This takes months, sometimes years, to fully elaborate to the point of standing. To fulfil the potential of balance on two legs rather than four (commonly termed *upright bipedal posture*) and walk (refining *unipedal* balance) takes time, and the human pelvis develops gradually over the first six years of growth in response to these efforts and their cumulative loading patterns. The pelvis is a cartilaginous ring in the neonate and slowly but surely stiffens and hardens into bones as a direct result of force-transmission, animating the required minerals to be laid down as denser material, i.e. bone, as the baby becomes a toddler and eventually runs around as a child. The forming of the pelvic ring (as bone) is the result of forces transmitted through the form.

Figure 9.4

We can actually consider the back of the body as a sequence of curves; considered to be primary (formed in utero) and secondary (formed ex utero) that form as we develop. The front of the body is a continuum of this principle, if you consider we are formed in the round. (see Fig 9.2A)

Curved Poles

What if we start from an imaginary curved pole through the middle of the body instead of a straight one? *The laws of movement governing curved poles are very different from straight poles.* Furthermore, the biotensegrity model challenges entirely the notion of levers, which apply to linear structures. A standard lever, such as classically described for the movement at the elbow, for example, is represented as a "2-bar open chain mechanism" (Fig. 9.5). This

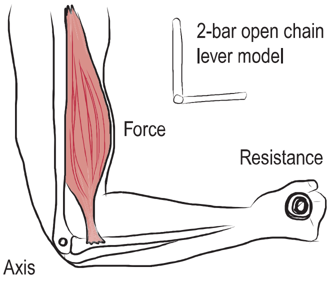

Figure 9.5

A lever is an open two-bar chain, shown here as a model for the arm (notably excluding other joints and structures), where the Triceps and Biceps muscles act over the upper limb bones to form a lever between them.

One of the not uncommon misunderstandings presented in movement research is the distinction of hopping. Some animals "hop" on two (hind) legs. Human beings hop on one leg. The same word means different things depending on the species it is applied to. When we walk, although the transition is seamless, the balance is unipedal. If we learn to sprint, we effectively animate a series of powerful (one-legged) hops, in joined up kinaesthetic writing, at increasing speed. Rabbits (and Kangaroos) hop using both their *hind legs* as one. In running, animals are also unipedal, even if they look

refers simply to the fact that there are two bars (the upper and lower arm) and one pin (the elbow) representing a (pinned) hinge joint. There are none in healthy bodies.

Living tensegrity architecture explains how forces move through the form of a living structure, joined together as one global architecture – like us. We are seeking explanations for *what we can actually do in a yoga classroom*, which far exceeds the limitations and range of lever mechanisms. We do not move in straight lines with levered joints, which don't exist anywhere in the body, however popular the term has been in the last four centuries of literature. In Jaap van der Wal's tissue-sparing dissection of the elbow, there was no angle at which the entire joint architecture was *not* under tension. This expands the context to a new explanation that can be found in "closed kinematic chains"[20,21] (see margin note and Fig. 9.6).

From the ground up, closed kinematic chain structures [**closed** (*because the body functions as a closed, enclosed system*) **kinematic** (*geometry of motion*) **chain** (*interlinked*) **structures** (variations on the connective tissue theme)] give rise to multidirectional and unpredictable motion patterns that describe what happens on a yoga mat, in more variety and detail than many classical theories can account for. In considering some of them, the reader is invited to explore from experience and read further (see suggestions for further reading at the end of this chapter). In Part C, we will consider these questions applied to adjustment in yoga specifically. They change the viewpoint considerably, from classical to connected biologic forms.

As human beings, we might organise from a "centrifugal sense", or a "centripetal" sense; however, there is no straight vertical axis for the body in its physical experience; we do not self-assemble as a compression-based architecture. The spine is curved. Our "null point" of embryonic development (see Ch. 4) forms ideally into a changing, continuous S-shape (just as Leonardo da Vinci first drew it (see Ch. 2). We can use it as an upright *reference* but that is a balancing act in itself. We can say we "straighten it"; however, its default design is a series of beautiful curves that allow us all the privileges of helical motion. (See Ch. 14, A Simple Practice, where we consider this in practice.)

"Developing a deeper appreciation and understanding of the helical nature of human anatomy through dissection is now further supported by modern day imaging techniques including ultrasound, MRI, and tensor magnetic resonance linking morphology and function to the true nature of our structure. New imaging techniques allow us to see what is not always possible to visualize immediately with the naked eye. We know bacteria exist however we cannot see them with the naked eyes. The same can be said for the most delicate of fascial laminas visible only (initially) by modern day imaging technology. Understanding fascial planes leads to less invasive medical and surgical clinical procedures. This results in faster recovery and retained functionality. With appropriate knowledge of fascia, the Yoga teacher can also play an important role in pre and post-operative care of patients ensuring a return to normal functionality and pain free movement"[22]

as if they are stamping from front to back legs. If you watch a cheetah (or a horse) running in slow-motion capture, you will see that each leg touches the ground in sequence, one-at-a-time. So, too, the rabbit's forepaws meet the ground one-at-a-time – does that mean they are really tri-pedal?

People are made up of three-dimensional shapes occupying space in roundish forms (tube-shaped volumes, essentially). We are tubes within tubes, folded to form various architectural origamis that are mostly able to change and modify, within a range, in a balance of motion, internal motility and poise. We are constantly interpreting (from "inter" meaning "between" and "translate" – *translate between*) internal and external forces in graceful balance, *all the time*. The geometries of living tensegrity architectures and the adaptable fabric of the fascia are the common denominators of all these forms. Notions of biomechanics dependent on flat planes, straight lines and exact symmetries (or spinal stacks) were originally deduced, at least in part, from dead bodies that were moved by the anatomist, rather than on observation of (or the technical ability to measure) living forms that animate themselves. The difference between the two conditions is vast, however established the linear, right-angle theories are of hard-matter forms. Recognising this changes completely the basis upon which we teach and read motion patterns. Once the spell is broken, we can wake up and cross the Rubicon towards new distinctions.

We have to actively *stabilise*, establish, release and *re-stabilise* ourselves from moment to moment (as anyone holding a yoga pose, for even seconds, experiences). It is an integral part of our movement skills; so how can we make sense of that architecturally? We become deeply interested in spiral balance and elastic recoil. In Chapter 10 we will look deeper into elasticity and make sense of this as our experience as a pre-stressed, non-linear, biologic system that changes itself (as a whole) from one moment to the next, just by breathing, just by being alive. It harnesses a new and valuable logic for the contemporary yoga teacher, to guide adjustment and honour natural, animated movement.[23]

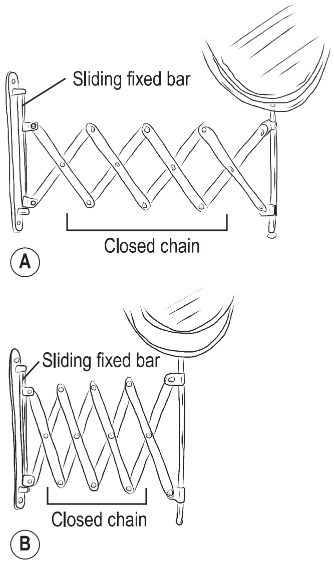

Figure 9.6

This is a four-bar linkage system with a fixed bar (where it is attached). It can squeeze together and open out (given its sliding hinge at the fixed bar) and remains in a closed kinematic chain. The "levers" are all joined up to form an enclosed linkage system that, in this symmetrical example, has the properties of a lattice. In a steam engine, the bars have different lengths, as they do in biologic systems.

Why Levers Give Way to Lattices

From classical, quantitative theories of motion, levers were devised as an explanation for how we move, joint by joint. In the absence of connective tissue, a lever (a two-bar open chain linkage) answers the question of a muscle moving a bone at a joint, like a hinge, in one plane – in a very simple mechanism. This would give rise to the classical theory of antagonistic pairs of muscles to balance and counterbalance the lever. (It also *appears* to satisfy Newton's third law that to every action there is an equal and opposite reaction.) But we now know we do not (ever) move one muscle at a time (or even just two, one on either side of a joint) and we do not move one joint at a time either. This is a "local" reductionist view (of a mechanical lever-arm puppet-like construction) and it is a struggle to make sense of it in describing the natural context of global biomotion, in the living, soft tissue, human body.

In Figure 9.7B, for example, the model is doing a typical squat. What is actually happening here is a co-contraction of muscles (if you stop at the local forces) in which the following is taking place:

> *"When sitting, our rectus femoris, the largest of the quadriceps muscle group, is hypothetically in a shortened phase as the hip is in a flexion phase. Rectus femoris runs over the anterior aspect of the flexed knee enveloping the patella and associating with the tibial tuberosity by means of the patellar*

Figure 9.7A

This classic dead-lift involves a co-contraction of both Quadriceps and Hamstring muscles (see text) that challenges the lever theory; no muscles are relaxed in either leg.

Image adapted by Bex Hawkins, with grateful thanks to Unsplash/Sergio Pedemonte.

ligament. It is, therefore, hypothetically lengthened at the knee when sitting but shortened at the hip. Meanwhile the hamstrings are lengthened at the hip and shortened at the posterior knee. When we move from sitting to standing our hip must extend and our knee must also extend. Rectus femoris therefore hypothetically elongates at the hip and shortens at the knee. John Cleland MD was Professor of Anatomy and Physiology at Queen's College, Galway, in Ireland from 1863 until 1879. It is interesting to read Dr Cleland's amazing paper entitled 'On the actions of muscles passing over more than one joint', in which he wrote ' ....I have made the measurements of the distance from the superior to the inferior attachment of the gastrocnemius muscle, when both knee and ankle were completely flexed, and when they were both completely extended, and have found that the distance remains unchanged. If we sink upon bended knees, flexing the limbs completely and remaining balanced on the toes then to rise to our full height on tiptoe, the length of the gastrocnemius remains unchanged in the movement'. From the biotensegrity-anatomy of the 21st century viewpoint these are classical examples of how tissues neither lengthen nor shorten but rather shape change throughout range of *motion similar to prismatic architected materials changing shape and reconfiguring their morphology without any individual part becoming shorter, longer, wider or narrower. This calls into question the idea of 'agonist' and 'antagonist' from the classical neurological description (i.e. when an agonist contracts its antagonist relaxes).*"[24]

Figure 9.7B

The tensegrity model is not trying to "be" a body. It is a model. The issue the protagonists have with classical biomechanics is that we forget a classroom skeleton is a model of *how the bones would arrange, if the connective tissue was still in place.* Quite how we allow ourselves to pretend that the absence of that tissue can be ignored, should raise alarms at every level of anatomy training. Tensegrity models do not pretend to represent connective tissue or bones *per se* – rather the manner in which they self-organise, via optimum force transmission. It offers a model of resistance to elastic deformation (see Ch. 10).

In a Tensegrity model, the "lines" of both the compression struts and the tensional strings represent *lines of force transmission in the living structure*, not lines of form. It is possible to make extremely complex models that more closely re-iterate the forces moving via the paths of least resistance to *dissipate* through the form, than actually pretending to *be the form.* A typical tensegrity model (the T-icosa - see Figs 10.6 and 10.7) isn't a muscle and bone model. It is a model of tension and compression **forces** inside a closed-kinematic chain system, one that constantly changes in our bodies, depending upon which movements we are making, where the loads are and how they can be optimally distributed. It demonstrates how we bounce back, running across a field (or jumping on a trampoline, or hurdling) or doing a Vinyasa Flow sequence on a mat. We don't succumb to the laws of plastic deformation or deform, like a fluid substance that takes the shape of its container. We retain our natural elastic *reformation* by moving about with ease, adapting moment-to-moment. Just like the tensegrity model, that bounces back (see Ch. 10, The Elastic Body).

Perhaps one reason it is so complicated to learn about levers and human "bending moments" and classical biomechanical explanations of movements is because levers do not represent what actually happens in moving humans. After all, these theories were deduced when the omnipresent and ubiquitous fascia was routinely discarded by anatomists. Deduction was made in the absence of the connectivity and continuity of force transmission we rely upon *to move*. We incorporate more intelligent means of leverage; as we have noted repeatedly, **there are no levers in biologic forms**.[25]

The key thing is that in the living body, unified, the webs form various types of lattices, or weaves, or helical envelopes or fractal polygons between structures, *on every scale*. Their range of motion or scope and type depend on where they are in our form and how they are used. That is "in the round". However you describe them, "straight they ain't" in the body. We cut and straighten the fascia out into flat pieces to examine it or look for straight connections to make diagrams of them, but that does not lend them linear mechanical properties *as forms*. It may even mislead us, as the samples are no longer connected and continuously enclosed, such as they would be inside the body. How do we account for that coherence?

Closed-Chain Kinematics

Everything in the body is enclosed and linked together by that which encloses it (fascia). Thus the "chains" of moving parts, if we call them such, are also continuously connected. If the chain is "closed", then the bars cannot be levers, by definition. They become what is called a four-bar (or multi-bar) linkage

In a closed kinematic chain (CKC) mechanism, to climb, for example, we have to get a minimum "fix" or temporary stillness from 3 limbs or points of contact. Then we are free to move the fourth limb, to create a new *triangulated position*. This is how insects move and how we climb walls or trees. Temporarily, we attach either one foot and two hands, or two feet and one hand, as the minimum (3-bar) CKC to the ground or the climbing wall. With that in place, we can seek the placing of the spare hand or foot, for the next triangulation pattern. Gradually that looks like motion over the surface, in a series of closed-chain still-frames. This is a four-bar or multi-bar CKC mechanism, which uses "three-ness" or triangulation, for temporary stability, to travel, but is not limited to it, to move. (See Ch. 13 for the geometry behind this.)

system, which happens to be the minimum to represent our movement. (Three-bar mechanisms are fixed – see margin note.)

The structure becomes self-contained and the control mechanism changes completely (in that the lever explanation becomes redundant). In a closed system, the control at one end is reiterated throughout the structure. In his article "The Scapula is a Sesamoid Bone",[26] Dr Levin suggests that the control of the arm and hand comes from the spine, via the shoulder blade (scapula), to the fingers. Thus, it can authorise the integrated movement and subtle coordination we appreciate, based on a model such as the four-bar or multi-bar linkage[27] system. If the hand and fingers were in a line or sequence of levers, the *least* control would exist at the distal end. We enter a much more sophisticated realm of geometry, congruent with our biotensegrity architecture, the one we share with all other living biological forms. It suggests the possibility of the kind of dexterity and variety we can enjoy; we have the *most* dexterity in our fingers and toes. It is something that makes sense of the postures, the way we do them.

Something magical begins to happen to the geometry of a structure at four bars (or more) in a closed linkage system. They acquire a shift in stability and enter a state of potential mobility at different angles and position, at higher frequency (see margin note for a simple explanation). The slightest movement is communicated throughout and affects the whole connected structure *because it is linked* structurally, everywhere.

Theo Jansen's structures[28] are made out of multi-bar chain mechanisms that are driven to ambulate with no batteries or motors, just the wind or the shape of the landscape. They help to demonstrate that forms (albeit sculptures) suitably connected as one closed system (animated by *external* forces) move in multi-bar linkages of a closed kinematic chain sequence. That is but one of our many resources. Neither Jansen's sculptures, nor our bodies, rely upon levers for motion. They don't have the subtlety of motion we enjoy, through our sensory, soft tissue, fluidic architecture – however they do demonstrate the essence of CKC motion and why it is an essential upgrade in sophistication over levers. The levers are invariably *part of* multiple closed linkages – not open two-bar chains, as if they could exist separately-but-tied-together to move a limb – they are never open at both ends. That makes no sense at all, when you appreciate that the image of an elbow, for example, is cut out from the approximately seven "levers-in-continuity" of the upper limb, from breast-bone to finger tips. "Joined-up levers" don't work the way we do – you cannot simply cut one out from the continuity it exists as (i.e. an entire limb) and then describe it as something it isn't! (Even if that has been done for 400 years, it doesn't mean it is accurate.) All bars in the body are closed chain mechanisms.

There is integrity of form and movement: any change is communicated and transmitted kinematically (i.e. through the geometry of the structure). Even when it is squeezed, the structure "closes" but it does not reduce to a straight bar or a lever. ***It multiplies up to a lattice.*** At the very least number of

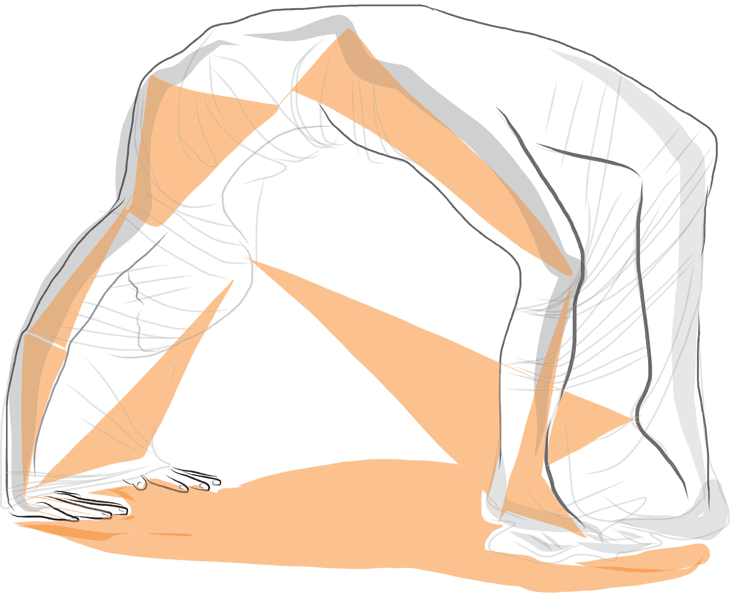

Figure 9.8

Through our yoga eyes, we see the whole movement, integrated via the fixed bar of the ground. It is seen in its entirety as a multi-bar linkage. The system is compliant and self-motivated – a closed kinematic chain.

dimensions (two) it is a woven fabric. If, as Kenneth Snelson[29] suggests, weaving is the mother of tensegrity, then a pathway of enquiry from a woven lattice (the fascial matrix) to a four- to multi-bar system (of architectural design) seems worthy of some careful research. In other words, when the fabric is connected to itself, it forms a tube, in 3D. When the tube moves through itself, it forms a toroidal pattern, that is considered to be 4D (see Chapter 10, Figs 10.1–10.4). It models the spinal disc pattern and many other aspects of the human structure.

A multi-bar structure such as a Hoberman's Sphere (Fig. 9.8) can "expand" and "in-draw" without losing its structural integrity (see Fig. 9.6) or inter-relationships. Five-bar systems have one fixed bar, from which the rest of the closed chain can be animated in a coordinated, intercommunicating way. Whatever movement occurs, despite the different amplitudes, the whole structure is part of the organisation *at all times*. That is what is so, on a yoga mat! (Or any other movement!)

If the bars in a closed kinematic chain have different lengths, they can modify the available shapes, movements, range and overall organisation that is expressible by the structure, in response to forces around or through it (see Jansen's models on the beach – further reading). However, they still remain intimately interdependent and related. With ball and socket joints added to the variety of frictionless hinges (like our joints, which van der Wal refers to as "*disjoints in the continuum*"), the arcs and ellipses they can describe become three-dimensional under control of the organising motor. If the spine is the central "motor" or "engine", as Gracovetsky suggests, then control of the limbs

What is a closed kinematic chain? Kinematic refers to the geometry of a structure, independent of the kinetic forces acting upon it. A closed chain means each link is attached at both ends. A lattice is an example of a closed kinematic chain, where every movement moves the parts, as a whole. The minimum number of bars in a closed kinematic chain is four. (Three bars give you a rigid triangle, that is a stable structure.) We are essentially unstable structures that actively self-*stabilise*. This too makes sense of our yoga. The work is not so much to be able to do a handstand, or one-legged posture, but to hold it there. A multi-bar closed-chain structure has one fixed bar, from which it moves the rest. (See the shaving mirror in Fig. 9.6, for example.) Consider the ground as our "fixed bar", changing every time we place ourselves upon it, depending on which part we place and where. Basically, we take the ground with us, wherever we move; *it is our fixed bar*.

can express the kind of patterns and shapes we *see when we move them the way we actually do* (which is never in a flat plane with a single pin at the joint, holding two bars together. It just isn't possible in a living organism – it is literally the wrong engineering terminology for round, living things that are invariably *volumes*).

When you consider the different shapes we make and balances we manage in a yoga class, the spine tells a much more mobile, multi-directional and intelligent story than a straight or stacked segmented pole can begin to account for. Our central "midline" is a "mid-wave" through a curved tube that allows us to do what we do on the mat, with all our helical movements and deep twisting and binding postures to account for; *as we breathe*.

We see three essential features of our movement patterns arising in a multi-bar closed-chain linkage:

- The structure is self-contained, enclosed and variable within the range of the one whole organisation.
- One "motor" can drive the whole shape economically. Nothing is redundant or separated from the whole form.
- Everything affects everything else in a self-regulating architecture, based on its innate shape and the coordinating angles and rod lengths of the closed chain.

> *"Biological linkages frequently are compliant. Often one or more bars are formed by ligaments, and often the linkages are three-dimensional. Couple linkage systems are known, as well as five, six and even seven-bar linkages. Four-bar linkages are by far the most common though."*[30]

In biology, many creatures favour a closed kinematic chain structural arrangement based on four-bar linkage, such as the jaw dynamics of many fish. D'Arcy Wentworth Thompson[31] showed this as the basis of variation in species, in his work *On Growth and Form*.[32]

A perfect and obvious example (one of many) in our bodies is the knee joint, which attaches the upper leg bone (femur) to the lower leg bone (tibia) by the cruciate ligaments. These are referred to as an X-bar arrangement.[33] (See Figs 10.1–10.4 in Chapter 10, The Elastic Body.)

A linkage designed as a network, such as our body matrix, models a closed kinematic chain. As referred to earlier, one bar in such a system is fixed; from this the closed chain can move as a whole. Our fixed bar is the ground. We ourselves are not fixed. We are indeed compliant, but we can change our whole arrangement from moment to moment by incorporating the ground differently as we move (see Fig. 9.8). Effectively, we take the ground with us wherever we go on earth, using it under and between the parts of us on its surface, as we need to at the time. As Gracovetsky suggests, we exploit gravity to our energetic advantage.

Please see references on following pages

Table 9.1

Classical model	*Contemporary model*
Parts (cogs – bio-mechanical)	Whole (re-cog-nise – bio-motional)
Compression	Biotensegrity (tension–compression)
2D diagrams (duality)	3D holograms (triunity)
Two-bar levers and pendulums	Four-bar and multi-bar linkages
Open chain mechanisms	Closed kinematic chains
Divided down into planes	Multiplied up into containers
Linear biomechanical systems	Non-linear biologic systems

Ch. 12) and can be found in the drawings of the Sacred Geometry studied by philosophers and architects referred to in Chapter 2. Perhaps we are exploring a unifying process beyond the limits of dualistic thinking, the rebirth of what yoga actually stands for and a return to a deeper understanding of ancient wisdom.

Further Reading

The spinal engine theory put forward by Serge Gracovetsky, PhD, is explained and illustrated in very accessible form in Erik Dalton's book *The Dynamic Body* (Erik Dalton, *The Dynamic Body*, Freedom from Pain Institute, Oklahoma, 2011; http://erikdalton.com/). Gracovetsky originally published his theory in 1987 and updated it in 2008. See also Appendices 6 and 7 of his 2010 publication *Non-Invasive Assessment Of Spinal Function Automatizing The Physical Examination: An Application Of The Theory Of The Spinal Engine*. Appendix Six discusses the concept of stability, an issue of importance for the determination of best posture, including the role of the sacroiliac joint. Appendix Seven explores the importance of the coupled motion of the spine and its application to sports medicine. The book is available from the author (gracovetsky@videotron.ca); from Amazon; or from the publisher (www.lulu.com). Space does not permit reproduction of any of it here but it is well worth further research by the reader. See also https://sites.google.com/site/gracovetsky/home for details of other publications by Serge Gracovetsky.

Stephen M. Levin's website (www.biotensegrity.com) contains various articles examining the logic of closed kinematic chains and how our bodies elaborate this model.

Graham Scarr's website (www.tensegrityinbiology.co.uk) is full of highly informative articles and illustrations. It also includes models of the geometry behind the forms, referred to as Geodesic Geometry: see *Biotensegrity - The Structural Basis of Life*, Handspring Publishing, Edinburgh, 2014.

Theo Jansen is from Holland. In 1990, he began building large mechanisms based on closed kinematic chain principles, made out of PVC (and more recently 3D printed on a smaller scale) that are able to move on their own propelled by the wind, or the shape of the land. They are called (collectively) Strandbeest. They are kinetic sculptures that appear to "walk". The original designs are hand built on a large scale by the Dutch artist, based on closed kinematic chain movement principles. www.strandbeest.com. Smaller ones have been made in 3D printing.

See also papers referenced below in specific links, in the text.

Notes

1. Stephen Levin, http://www.biotensegrity.com/resources/tensegrity-truss-spine.pdf: "The Tensegrity-truss as a Model for Spine Mechanics".
2. This is a phrase used powerfully by one of my mentors, Caroline Myss, PhD. It actually comes from the era in which Julius Caesar defied orders and "crossed the (river) Rubicon" back into Rome, to form what became the Roman Empire. The word Rubicon comes from the same root as "ruby" referring to the red soil of the region. Needless to say it is a symbolic reference to a huge sea-change in motif and motivation.
3. http://www.fasciacongress.org/2007/. Serge Gracovetsky, Fascia Congress Part #1 of 3, Boston 2009.wmv. Available on You Tube (with parts #2 of 3 and #3 of 3).
4. Serge Gracovetsky (1997) Linking the spinal engine with the legs: a theory of human gait. *Movement, Stability and Low Back Pain – The Essential Role of the Pelvis*.
5. Stephen Levin (2008) Human resting muscle tone (HRMT): narrative, introduction and modern concepts. *Journal of Bodywork and Movement Therapies* 12:320–332.
6. Serge Gracovetsky: his presentation on the spinal engine theory given in Brighton, England, in September 2011.
7. See Chapter 6 for detailed explanation of *ground reaction force*, equal to the body's mass.
8. Ibid.
9. See Appendix A, *Bone is Fascia* by Stephen Levin.

10. John Sharkey (2019) Regarding: Update on fascial nomenclature-an additional proposal by John Sharkey MSc, Clinical Anatomist. *Journal of Bodywork & Movement Therapies* 23(1):6–8.
11. Chris Jarmey and John Sharkey, *The Concise Book of Muscles*, Third Edition. "Biotensegrity – Biomechanics for the 21st Century", J. Sharkey and Stephen Levin, p. 50
12. A.T.Masi, J. Hannon (2008) Human resting muscle tone (HRMT): Narrative introduction and modern concepts. *Journal of Bodywork & Movement Therapies* 12(4), 320–332.
13. Vanda Scaravelli, *Awakening the Spine*, 2nd Edition, Piner and Martin, London, 2011.
14. Stephen Levin: www.biotensegrity.com
15. Serge Gracovetsky; see suggestions for further reading. See also https://sites.google.com/site/gracovetsky/home.
16. Ibid.
17. Stephen Levin, et al (2017) The significance of closed kinematic chains to biological movement and dynamic stability. *Journal of Bodywork & Movement Therapies* 21(3):664–672.
18. Serge Gracovetsky's spinal engine theory; see suggestions for further reading, below, and https://sites.google.com/site/gracovetsky/home.
19. Leonid Blyum (www.abrtherapy.com/team-member/leonid-blyum/) refers to the secondary parts of the upright "S" as "super curves" rather than demoting them to the term "secondary". Since they give rise to a much greater range and articulacy of movement, it honours the advantage the spinal engine theory elaborates. Rather than suggesting they are less important, or secondary, this elevates the curvature at the neck and waist to the assets it bestows on our range, elasticity and natural style of motion.
20. Graham Scarr, www.tensegrityinbiology.co.uk, article: "Geodesic". See also*: Biotensegrity: The Structural Basis of Life*, Handspring Publishing Ltd., Pencaitland, 2014.
21. Stephen Levin, et al (2017) The significance of closed kinematic chains to biological movement and dynamic stability. *Journal of Bodywork & Movement Therapies* 21(3):664–672.
22. John Sharkey (2018) Biotensegrity-Anatomy for the 21st Century Informing Yoga and Physiotherapy Concerning New Findings in Fascia Research. *J Yoga & Physio* 6(1):555680.
23. Karen Kirkness, MFA, MSc, *Spiral Bound: Integrated Anatomy for Yoga*. Handspring Publishing Ltd, Pencaitland. In press – due 2021.
24. Centre for Anatomy and Human Identification, School of Life Sciences, University of Dundee, Scotland. John Sharkey Keynote Speech at the Massage & Myotherapy Australia National Conference at the Gold Coast in June 2018. Excerpt from: *Massage & Myotherapy Australia* (Summer 2017), "Myths and realities: The only word? The last word? Musings and 'biotensegrity-informed' opinions from Clinical Anatomist John Sharkey MSc (BACA) concerning human anatomy and physiology."
25. Stephen Levin, personal communication, 2013.
26. Stephen Levin (2005) "The scapula is a sesamoid bone": www.biotensegrity.com. Letter to the Editor, published in the *Journal of Biomechanics* 38(8):1733–1734.
27. D'Arcy Wentworth Thompson, *On Growth and Form*. Cambridge, Cambridge University Press, 1961.
28. See Further Reading for links and website
29. Kenneth Snelson, http://kennethsnelson.net/.
30. Wikipedia, Biological Linkages, Linkage (mechanical).
31. Sir D'Arcy Wentworth Thompson CB FRS FRSE was a Scottish biologist, mathematician and classics scholar 1860–1948, Education: University of Dundee, Trinity College, The University of Edinburgh, University of Cambridge.
32. D'Arcy Wentworth Thompson, *On Growth and Form*. Cambridge, Cambridge University Press, 1961.
33. X-bar linkage reference in N. Farhat, V. Mata, D. Rosa and J. Fayos (2010) A procedure for estimating the relevant forces in the human knee using a four-bar mechanism. *Computer Methods in Biomechanics and Biomedical Engineering* 13(5):577–587.
34. *The Ease of Motion*. pp. 77–79.
35. R. Schleip, W. Klingler and F. Lehmann-Horn, "Active Contraction of the Thoracolumbar Fascia: Indications of a New Factor in Low Back Pain Research with Implications for Manual Therapy". In: A. Vleeming, V. Mooney and P. Hodges (eds), *The Proceedings of the Fifth Interdisciplinary World Congress on Low Back and Pelvic Pain, Melbourne, 2004*. T.A.H. Järvinen, T.L.N. Järvinen, P. Kannus, L. Józsa and M. Järvinen (2004) Collagen fibres of the spontaneously ruptured human tendons display decreased thickness and crimp angle. *Journal of Orthopaedic Research* 22(6):1303–1309.
36. Jian-Shan Wang, Gang Wang, Xi-Qiao Feng, Takayuki Kitamura, Yi-Lan Kang, Shou-Wen Yu and Qing-Hua Qin (2013) Hierarchical chirality transfer in the growth of Towel Gourd tendrils. *Scientific Reports* 3:3102.
37. Hans Kubler (1991) Function of spiral grain in trees. *Trees* 5:125–135.
38. Leonid Blyum (www.abrtherapy.com/team-member/leonid-blyum/) is the director of Advanced Biomechanical Rehabilitation (ABR). His extensive work and research in the practical application of biomechanical principles is richly documented through clinical experience and an advanced education in mathematics. He translates complex models into practical applications for practitioners and parents of children where rehabilitation is required and in the rehabilitation of complex syndromes where biomechanical function is impaired.
39. Vanda Scaravelli, *Awakening the Spine*, 2nd edition, Pinter and Martin, London, 2012.
40. Stephen Levin, http://www.biotensegrity.com/resources/tensegrity-truss-spine.pdf: "The Tensegrity-truss as a Model for Spine Mechanics".