Biomechanics & Theories of Human Gait

Tim Morgan, DC
Boston Sports Medicine Performance Group 2012

Collaboration: Knowledge Beyond the Guru

- *"We are like dwarfs on the shoulders of giants, so that we can see more than they, and things at a greater distance, not by virtue of any sharpness of sight on our part, or any physical distinction, but because we are carried high and raised up by their giant size."*

  Bernard of Chartres, 12th Century

- "*What Des-Cartes did was a good step. You have added much several ways, & especially in taking ye colours of thin plates into philosophical consideration. If I have seen further it is by standing on ye sholders of Giants [sic].*"

  Sir Isaac Newton, 17th Century

Giants, Antelope & Fruit

- There have been countless giants before us, and there are giants among us
- Giants (researchers, practitioners, coaches) have chased the antelope into hyperthermia and have provided us, the present day “hunter gatherers”, with low hanging fruit
- It’s up to us to prepare the meal and make some wine

Wanted: Paradigm Shift

- A well invested 4-5 hours: www.TED.com
- Search on "Collaboration" and listen to anyone who is smart enough to spend their time professing its virtues

- Alternatively, these links will get you started:
- Matt Ridley - When Ideas Have Sex
- Clay Shirky - Institutions vs. collaboration
- Noreena Hertz - How to Use Experts -- and When Not To
- Howard Rheinghold – The New Power of Collaboration
- Rachel Botsman – The Case for Collaborative Consumption

Teacher, Doctor, Coach, Therapist

- “A fool's brain digests philosophy into folly, science into superstition, and art into pedantry. Hence University education”

  \- *George Bernard Shaw*

- (To think about) “the importance of people who could stand at the intersection of humanities and sciences, and I decided that is what i wanted to do”

  \- *Steve Jobs, paraphrasing Edwin Land of Polaroid*

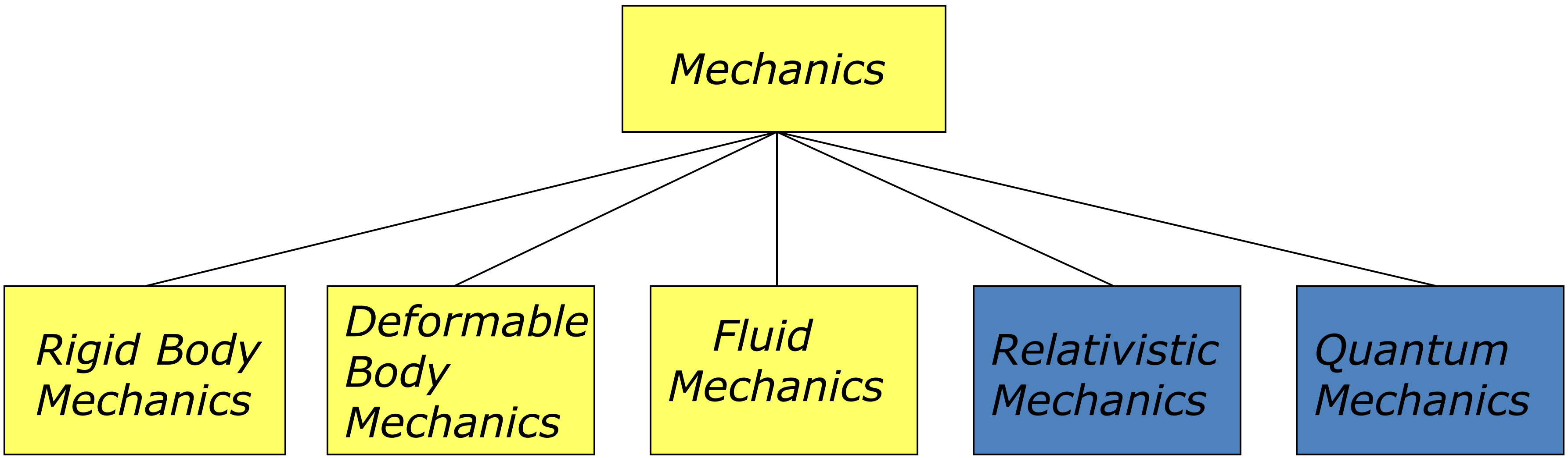
- "Any intelligent fool can make things bigger and more complex... It takes a touch of genius --- and a lot of courage to move in the opposite direction."

  \- *Albert Einstein*

I, Pencil

- I, Pencil is a “1st Pencil” narrative that provides a unique conveyance of the collaborative concept
- This classic essay was written by giant Leonard Read
- At first glance, the concept appears a bit corny, but the process of reading it is inevitably enlightening and inspiring.
- The essay commands a respectful attitude of all who have added to the collective learning process

Mechanics - *analysis of the action of forces on matter or material systems*

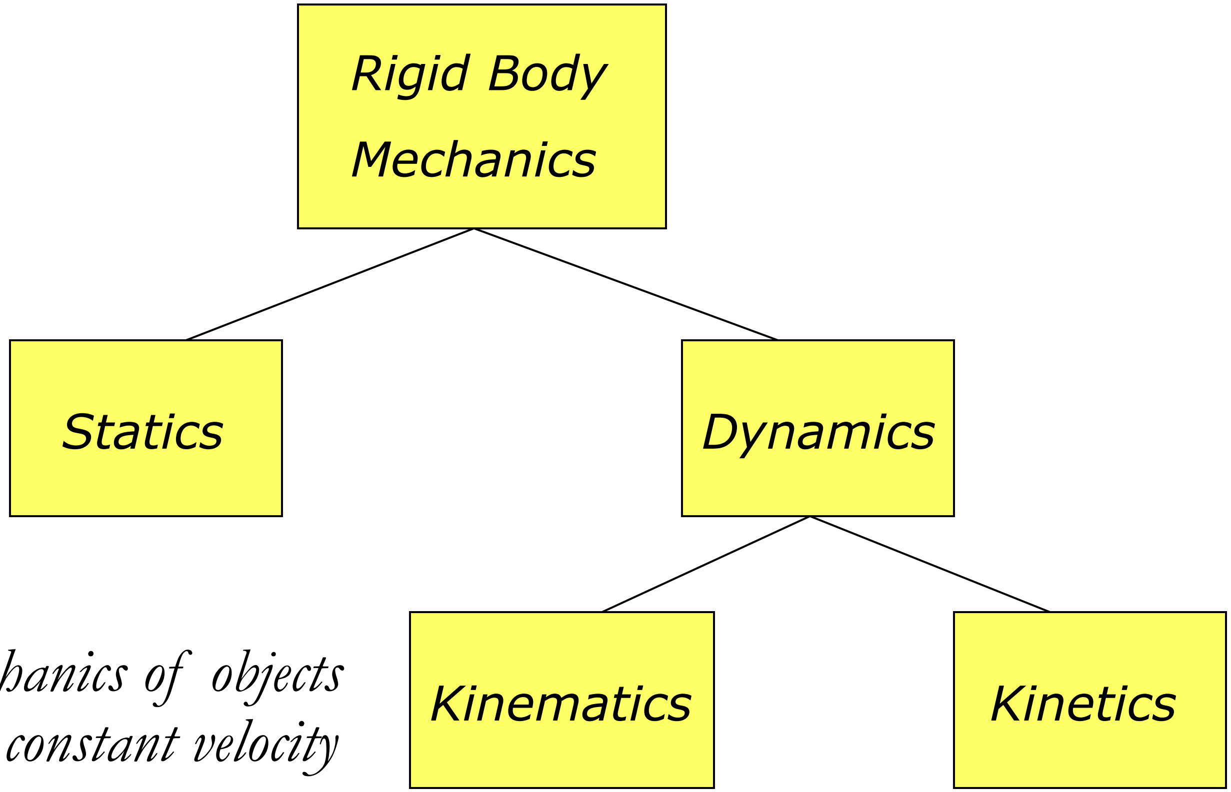


Rigid Body – *objects are assumed to be perfectly rigid*

Deformable Body – *objects can be deformed by a force*

Fluid – *Gas or fluid*

Branches of Rigid Body Mechanics



Statics – *mechanics of objects at rest, or at constant velocity*

Dynamics – *mechanics of objects in accelerated motion*

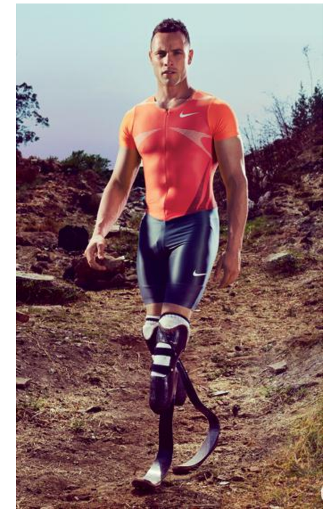
Kinematics – *describes the motion of a body without regard to the forces or torques that may produce the motion*

Kinetics – *describes the effect of forces on the body; i.e.. muscular force, gravitational force, external resistance force, ground reaction force, etc.*

What does Collaboration Have to do with Human Gait?

- Human gait is so unique, and so intricate, is it possible to comprehend it all by ourselves?

What Does Human Gait Look Like?



[Aimee Mullins]

[Oscar Pistorius]

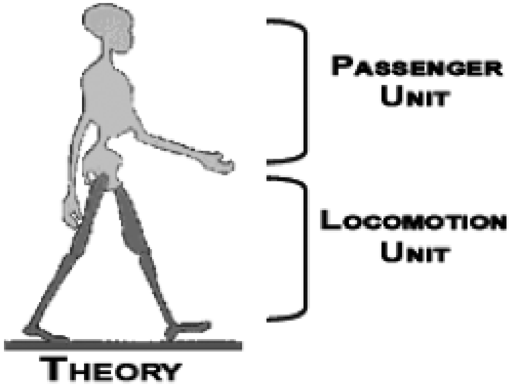
Gait Defined

- Gait – locomotion; the manner in which one ambulates

- Walking – a manner of gait characterized by a series of losses and recoveries of balance; sometimes referred to as controlled falling; as a hallmark, walking gait is marked by always having at least one foot in contact with the ground, and at times with a period of double support where both feet are in contact with the ground; 60% of the gait cycle is spent in a stance phase

- Running – a manner of bipedal gait that represents a natural progression from walking; the progression from walk to run occurs as a strategy to conserve energy; increasing velocity comes at an energetic cost; running typically commences at a speed of 2.1-2.2 m/sec (4.92 mph); as a hallmark, running gait replaces the double support phase of walking with a double float phase, where there is no contact with the ground; there is a series of single leg support and double float periods; running stance phase is limited to 40% or less of the gait cycle

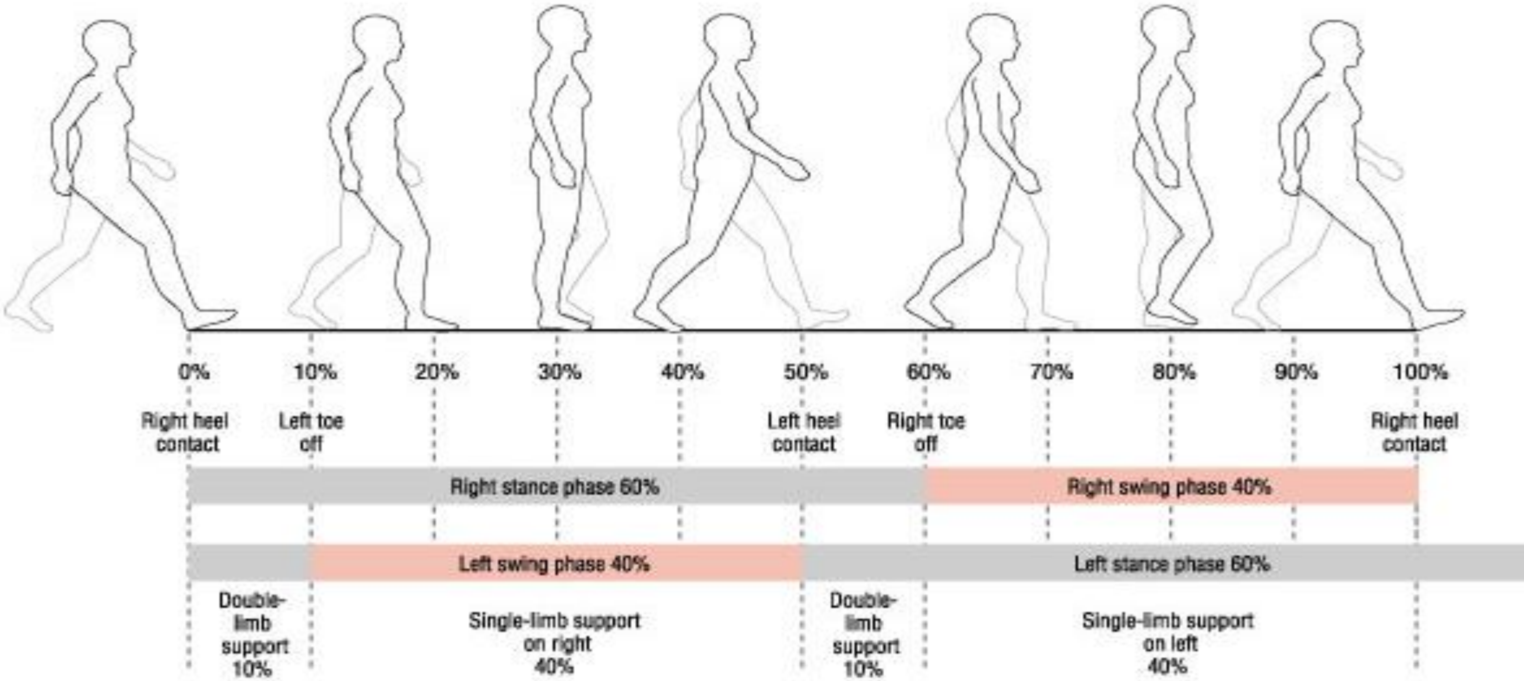
Pedestrian Theory of Gait



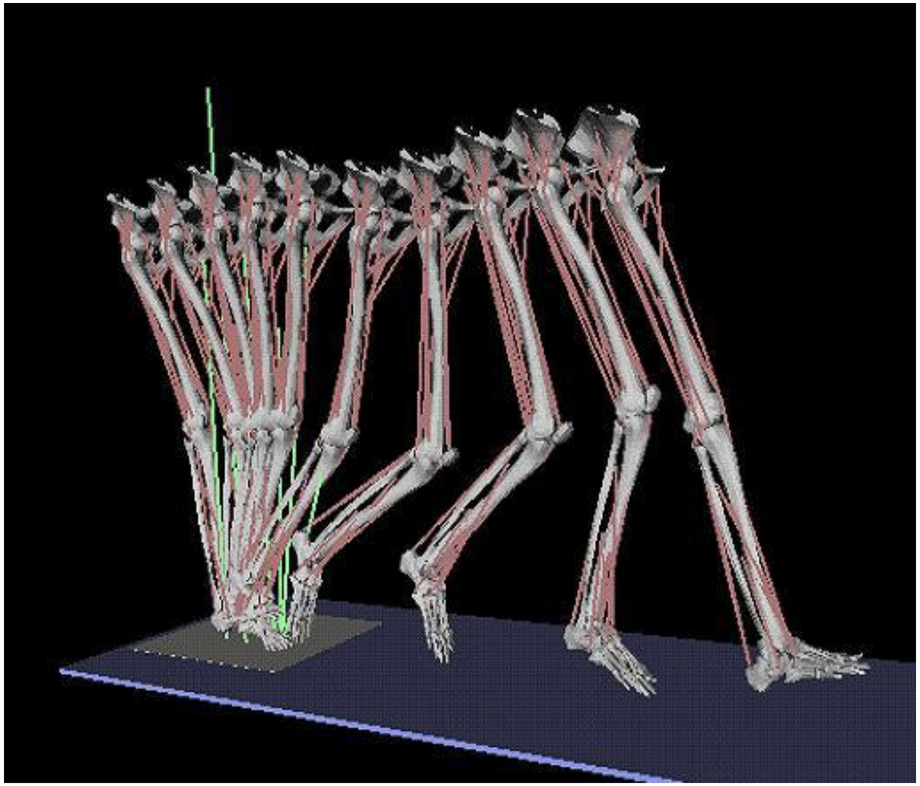
- **pe·des·tri·an** [puh-des-tree-uhn]
- 1. (N) a person who goes or travels on foot; wa
- 2. (ADJ) of or pertaining to walking.
- *3. (ADJ) lacking in vitality, imagination, distinction, etc.; commonplace; prosaic or dull*

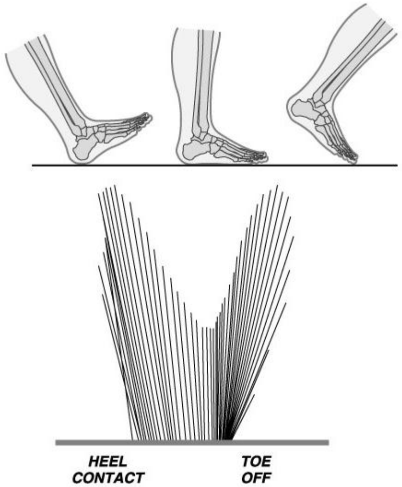
Pedestrian theory - A theory or perspective of human locomotion which prioritizes the observation and analysis of leg movement; this theory holds that the lower extremities are the primary tools by which humans ambulate; the trunk, head and upper extremities are considered "passengers"

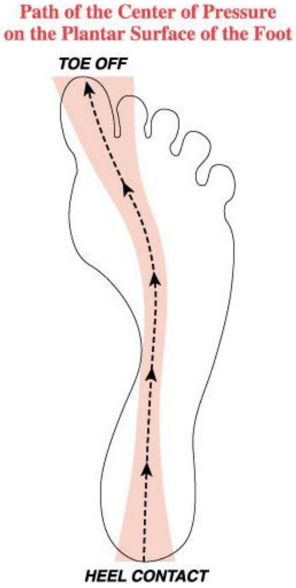
Phases of Gait



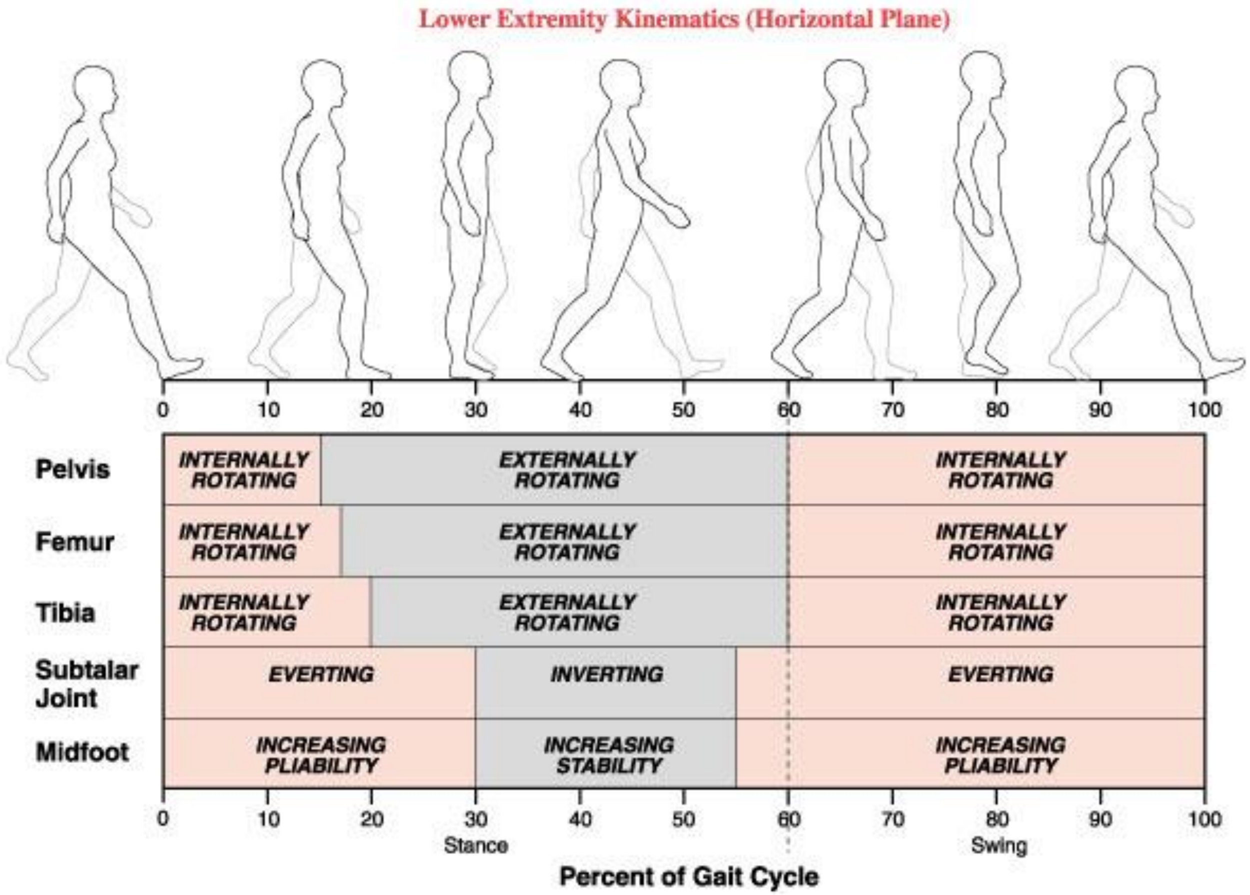
Loading & Propulsion Phases







Lower Extremity Kinematics

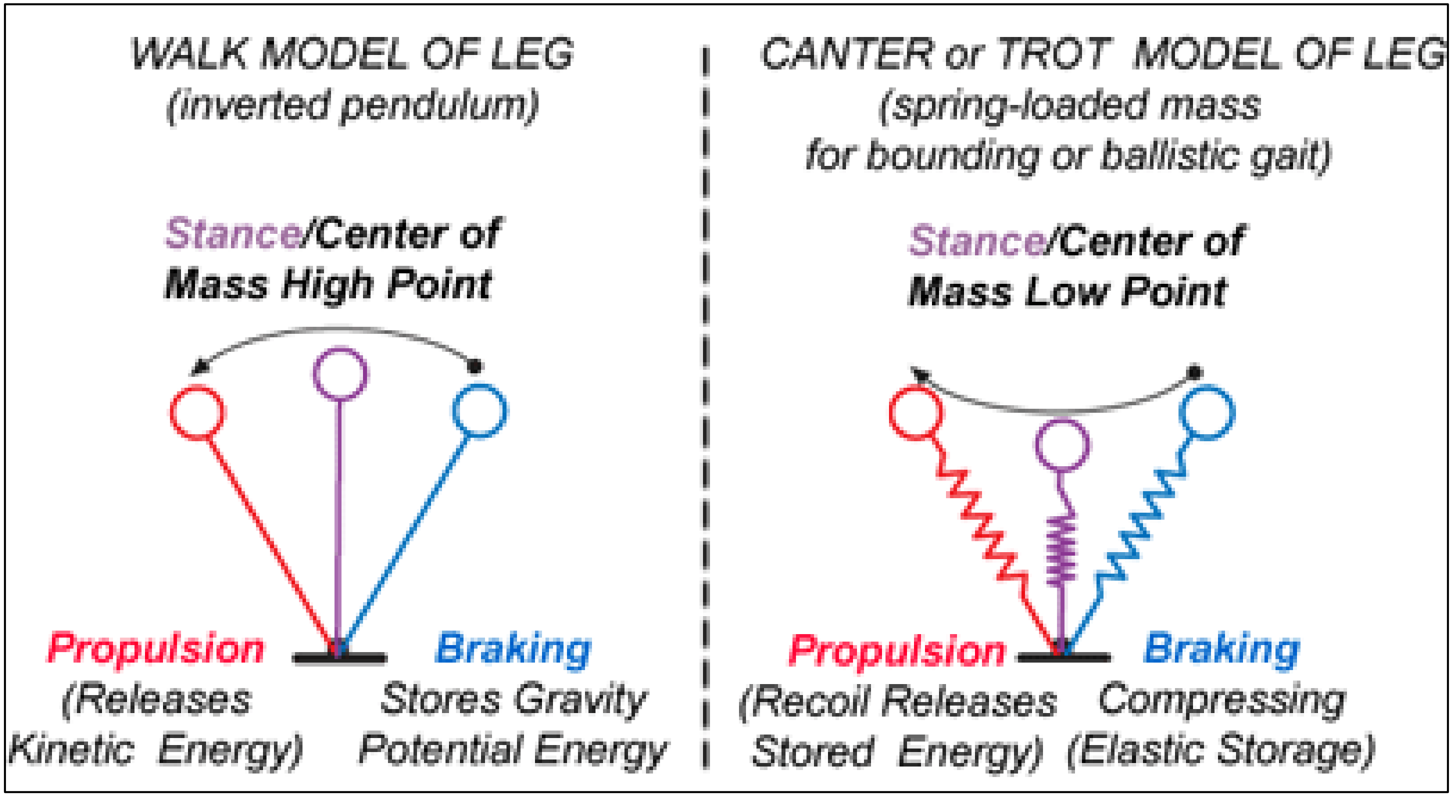


"IR", "everting" & "increasing pliability" kinematics can be considered lower extremity pronation; "ER", "inverting" & "increasing stability" kinematics is therefore lower extremity supination

Pendulum Theory of Gait

Minimizing of Energy Consumption

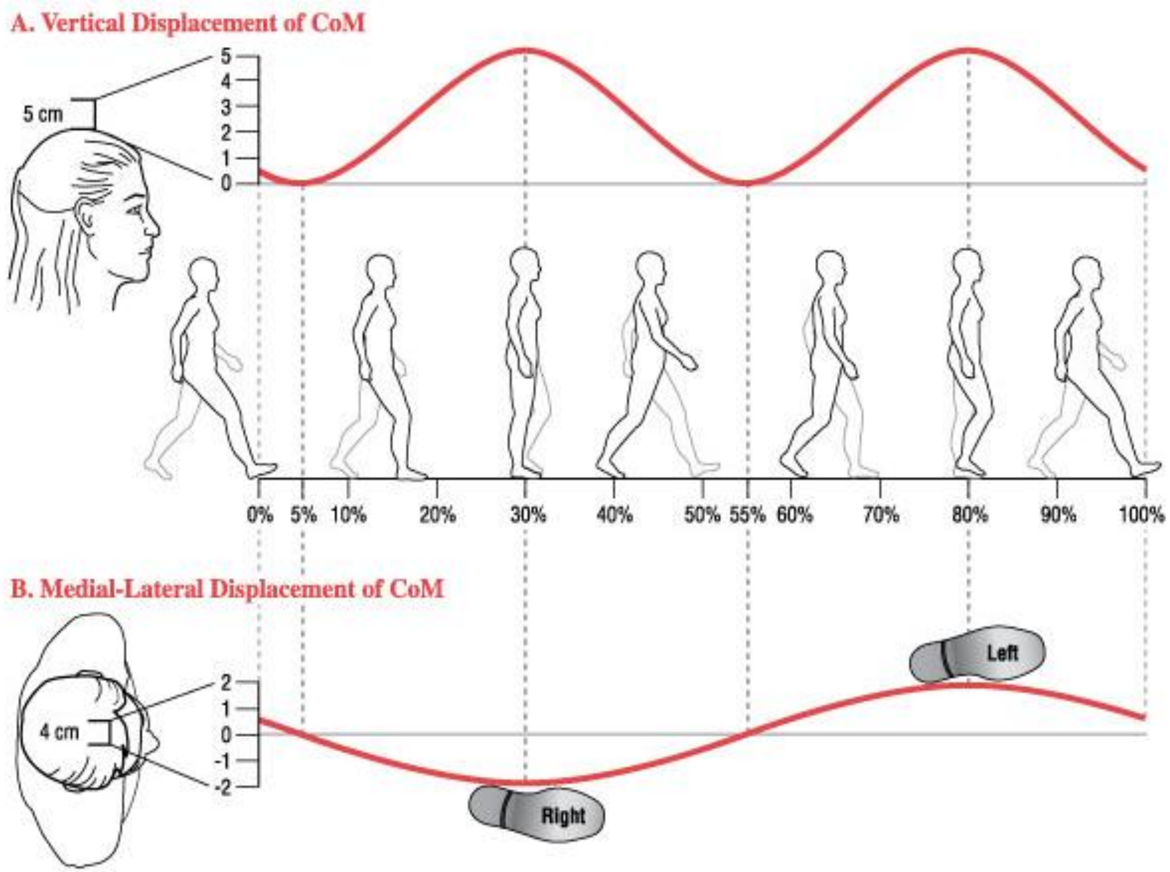
"PE & KE Resonating in the Gravitational Field"



"Pendulum Model" "Spring Mass Model"

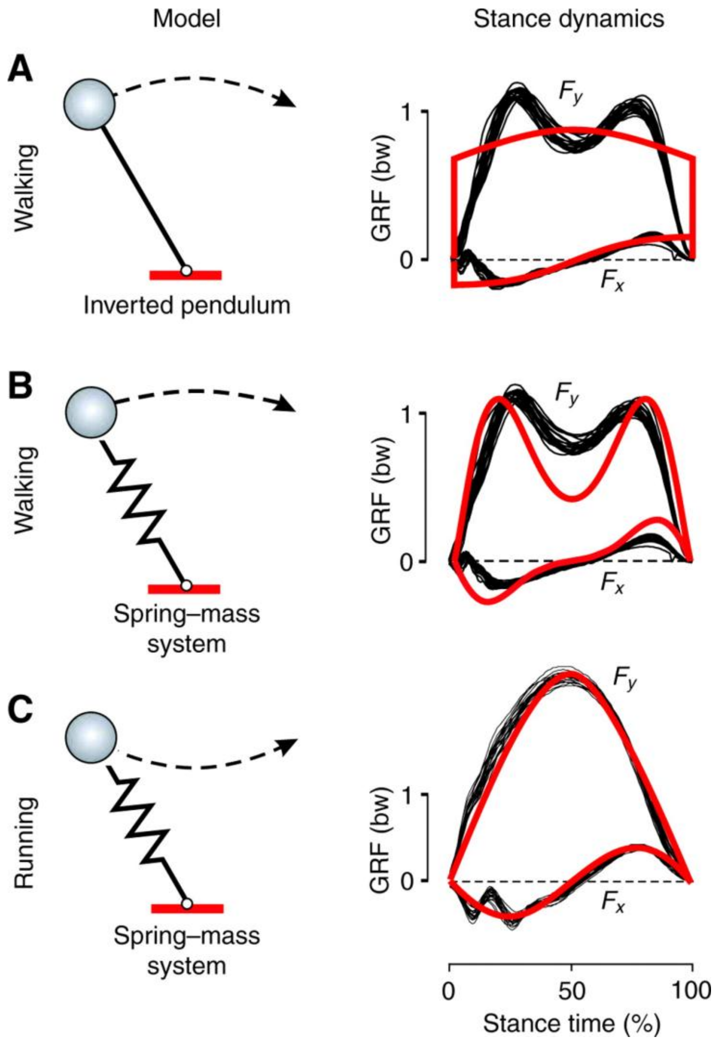
Reproduced with Permission: 7 April 2000: Vol. 288 no. 5463 pp. 100-106 DOI: 10.1126/science.288.5463.100 How Animals Move: An Integrative View. Michael H. Dickinson†, Claire T. Farley, Robert J. Full, M. A. R. Koehl, Rodger Kram and Department of Integrative Biology, University of California, Berkeley, CA

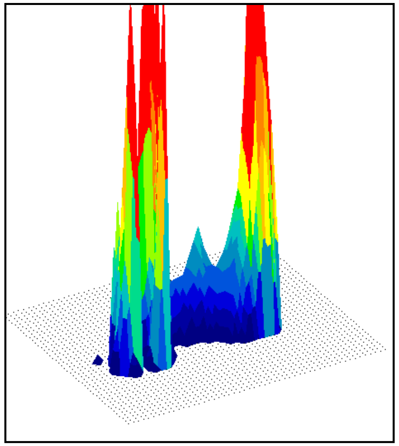
Resonating in the Gravitational Field



When both the vertical and medial-lateral displacements are considered together, the resultant path traveled by the COM should resemble a 'figure 8' configuration

Simple spring–mass models can reproduce key features of the dynamics of running and walking.





GRF Pressure Map of Walking

Roberts T J , Azizi E J Exp Biol 2011;214:353-361

The Journal of Experimental Biology

Maturation

Risk Aversion Hypothesis

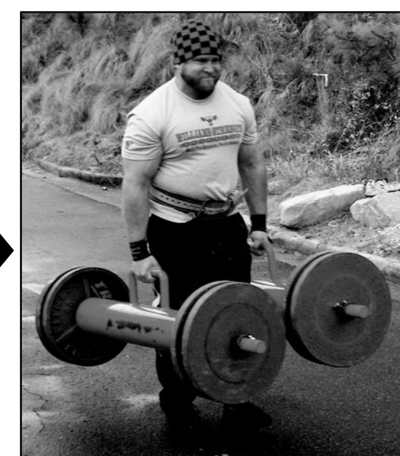
- When bi-pedal gait is first practice by children (~ 12-15 months of age), the initial strategy is to minimize the risk of falling
  - Wide base of support
  - Short step/stride length
  - Greater double limb stance phase
  - Higher cadence
  - Low velocity
  - No reciprocal arm swing
- This maturation process is thought to parallel the maturation of the child's CNS (coordination, confidence of movement) and musculoskeletal systems(muscle mass/force generation, long bone growth, hip angles, lumbar lordosis; lower extremity and spinal kinematics)
- Of interesting note is the similarity between a child's gait and that of the elderly

Locomotion Chronology (?)




A human infant from 3-6 months exhibits "creeping" type movements, largely driven by the LL. With progression to crawling, the complexity of movement increases to incorporate other myofascial lines and contralateral limb activity. This "cross crawl" mechanism serves as the foundational neuromotor programming for bipedal locomotion…..



Central Pattern Generators

"A dedicated network of interneurons in the spinal cord generates the rhythm and cyclic pattern of electromyographic signals that give rise to bipedal gait"

- Sten Grillner (1985) suggested that there are a neural pathways, which he referred to as "central pattern generators" (CPGs), that can be made to produce a rhythmic output.
  - Ex. Long standing spinal cord injury subjects were stimulated electrically, epidurally over the 2nd lumbar vertebral level; rhythmic, alternating stance & swing phases of the lower extremities were induced

- The CNS can, in a sense, simplify the immensely complex gait pattern by 'bundling' large numbers of neuronal signaling into just a few fundamental signals which control all the major muscle groups in both legs; the complex gait mechanism is afforded a certain automaticity

- Specific anatomic CNS locomotor CPG circuits have been identified in lower order vertebrates; and there is some mounting evidence to support the hypothesis that a single locomotor CPG controls both forward and backward walking
  - Ex. In an incomplete spinal cord injury patient, rhythmic stance and swing phases EMG patterns were generated by bringing the patient through suspended, externally induced stepping motions on a treadmill; sensory/afferent information to the spine reflexively generated gait cycle muscular activity. Locomotor Training Video Locomotor Training Video2

  - *"The very process of building knowledge transforms the hardware in which the knowledge is stored and operated."   (Matthew Syed, From "Bounce" a book about the 'talent myth' which extols the virtues of purposeful practice via the 10,000 hour rule)*

Neural Control & Mechanical Effect

- "*A Neural Network normally operates in two states: learning, where a process of changes in the synaptic weights occurs; and recall, where an input stimulus generates an output signal*" (Rumelhart et al., 1986).

- In this model, the neural system is the controller and the mechanical system is the effector; however locomotor training demonstrates that the effector can stimulate and trigger the controller; this elucidates the importance of proprioception and afferent signaling from the extremities; it also demonstrates the importance of the learning process and neuroplasticity

- Taga et al. created a mathematical model of bipedal walking that incorporated the neural system as a 'controller', and the mechanical system as the 'effector'; a pair of CPGs, modeled by an artificial neural network, controlled the muscles of the trunk and the lower extremities. Their biped consisted of eight segments, 10 degrees of freedom and 19 muscle actuators. Once the model had been trained, it not only produced level gait under normal conditions, but it also adapted to environmental perturbations such as uneven terrain or increased carrying load. The speed of walking could be controlled by a single parameter which drove the neural oscillators, and the step cycle could be entrained by a rhythmic input to the oscillators.

- *"remedial exercise is always time consuming, and time should not be wasted…We should not attempt to teach patients ideal locomotor patterns, but only correct the fault that is causing the trouble." karel lewit, MD (CraigLiebenson.com)*

Maslow’s Stages of Learning

Unconscious Incompetence

↓

Conscious Incompetence

↓

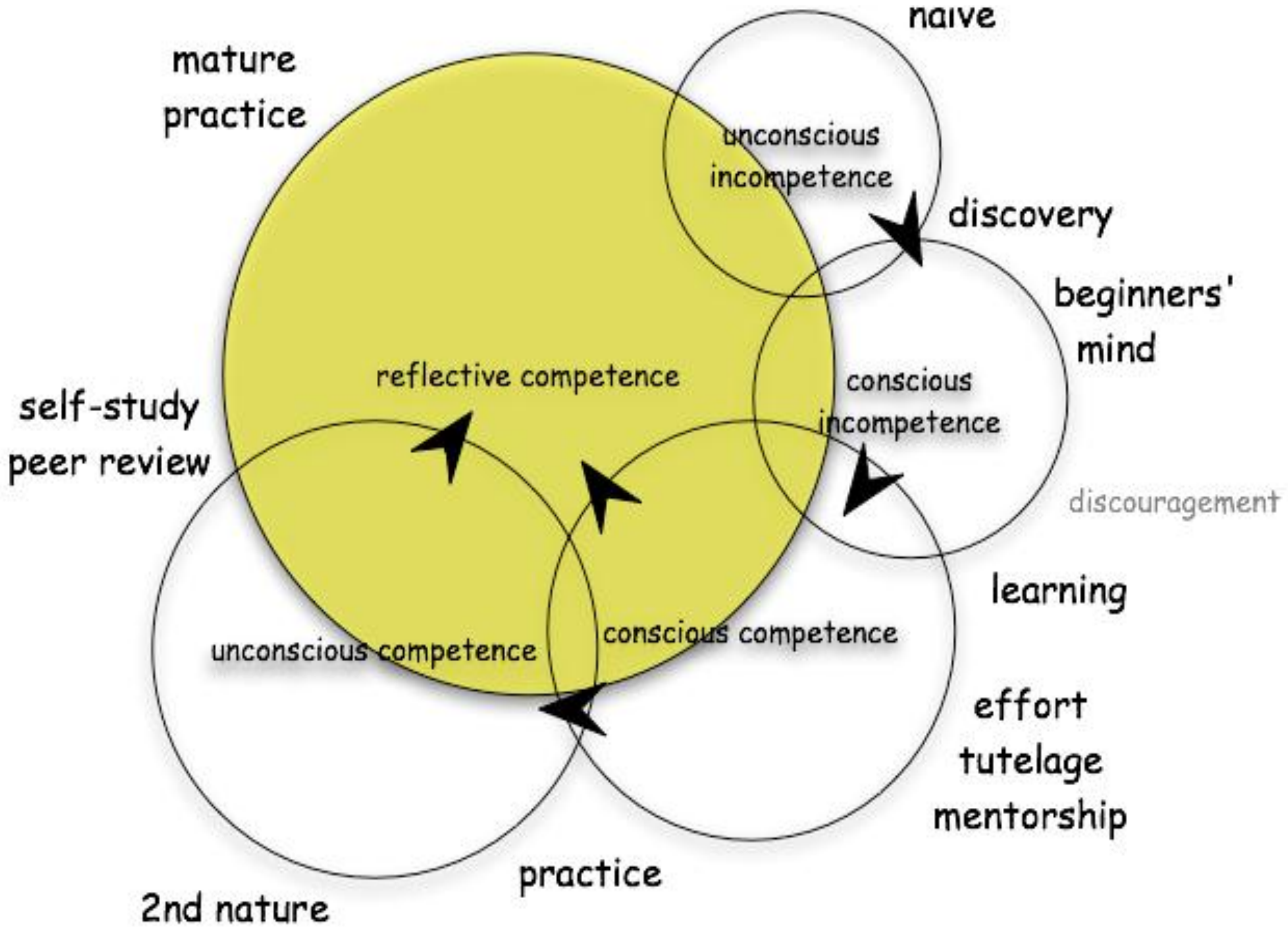
Conscious Competence

↓

Unconscious Competence

Maslow model

- Spine article of conscious adjustments to stabilization



What do we need in order to Walk?

Spinal Engine Theory of Gait

- **Spinal Engine theory -** A theory or perspective of human locomotion developed by Serge Gracovetsky, PhD which prioritizes the observation and analysis of thoracolumbopelvic biomechanics; this theory holds that woven into the human body 'design', is a fundamental biomechanical *coupled motion* mechanism which serves as the drive for human ambulation
- The spinal engine theory also assigns a supportive functional role to the lower extremities, in keeping with the theory of human evolution; Dr. Gracovetsky considered the legs as "instruments of expression"; and extensions of the spinal engine

Spinal Engine – Coupled Motion

A concept introduced in early 1900’s scoliosis literature by Robert Lovett, MD

- Coupled Motion is a second plane of motion that occurs within a joint system, part and parcel to the primary motion. Two or more motions are considered ‘coupled’ when it is not possible to produce one motion without inducing the second motion; spinal coupling is due to the morphological shape of the facet joint surfaces and the connecting ligaments and spinal curvatures
  - Ex. In the cervical and thoracic spines, left vertebral rotation (transverse plane) is coupled with left vertebral lateral flexion (frontal plane)
- Lumbar lateral flexion (frontal plane) is coupled with contra-directional vertebral rotation (i.e. right lumbar lateral flexion is coupled with left lumbar rotation
- The contra-directional coupled motion patterns of the various regions of the spine evolved for a reason; form fits function; the opposing directions of the coupled motion is synergistic

Spinal Coupling (cont.)

- It is this lumbar lateral flexion/rotation coupling that serves as the spinal engine 'drivetrain'

- Right lateral lumbar flexion will drive left rotation of the lumbar spine, and the pelvis

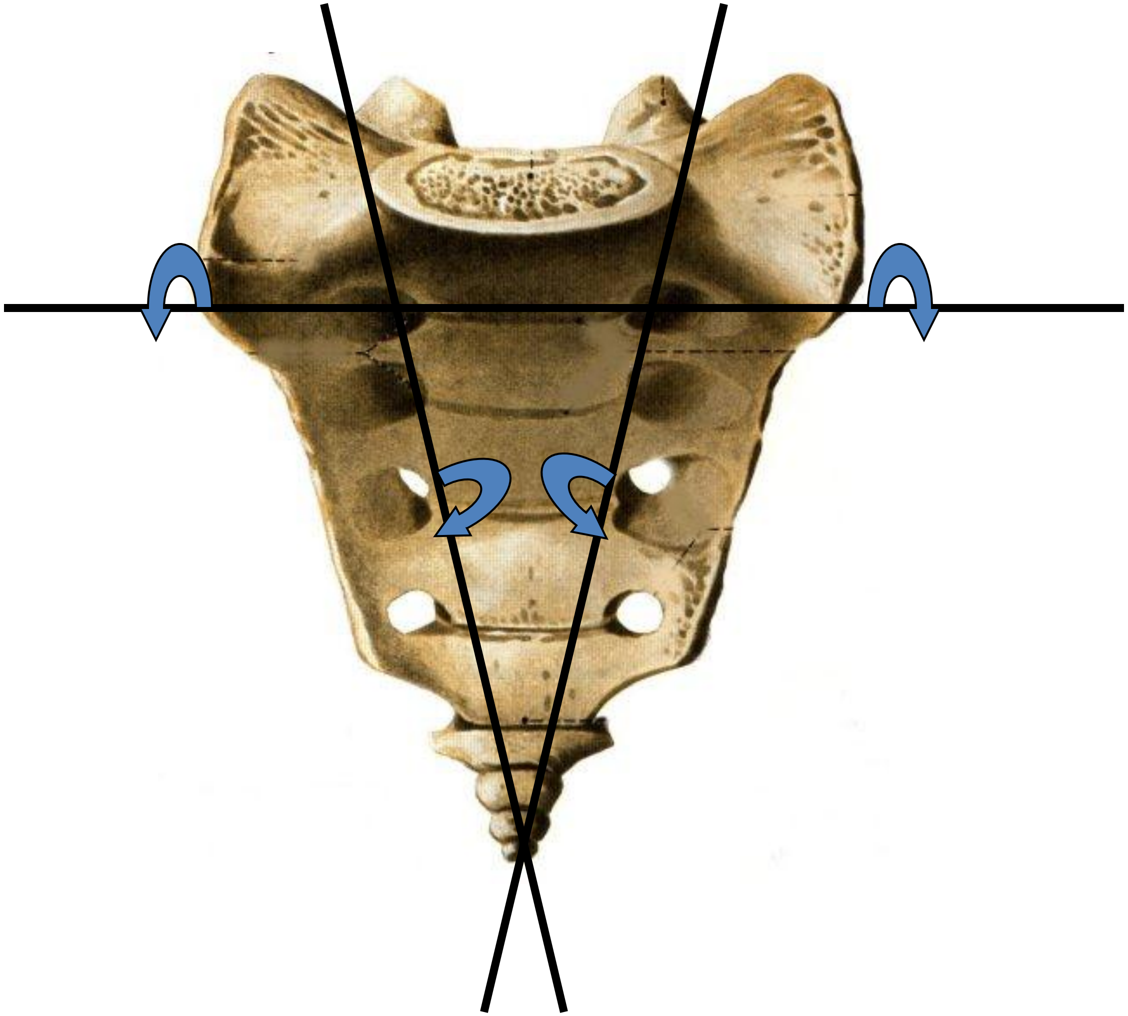
- Amongst bipeds, this fundamental lumbopelvic biomechanical mechanism is unique to humans; along with the subsequent kinetic and kinematic sequelae, this is what separates human gait from bi-pedality that is accomplished by other species

- This specific mechanism, during right legged weight bearing, the lumbar spine is pulled into right side-bending (& left rotation) by the multifidus, longissimus, iliocostalis and thoracolumbar fascia. This action counter-rotates the pelvis as the sacrum is forced into left side-bending and right rotation.

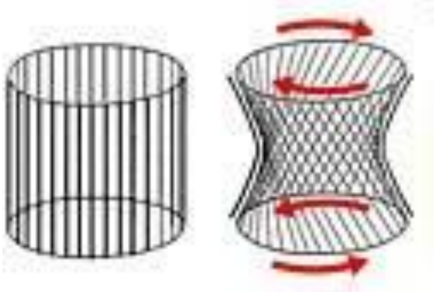
  – ***"A Flexed rod already bent in 1 plane cannot be bent in another plane without twisting"***

    (Lovett)

Tri-planar Sacral Nutation



Tri-planar sacral motion during gait is analogous to the action of paddling a kayak backwards



Dynamic Effect of the Thoracolumbar Fascia

Spinal Engine and Anatomy Train Synergy

Biceps Femoris and the Back Functional Line

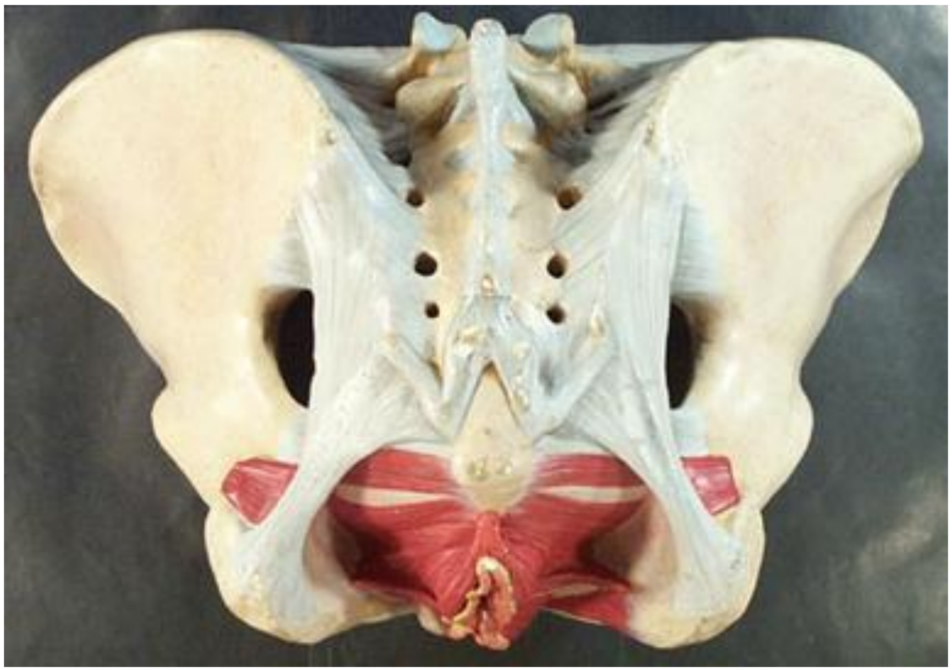
Superficial Back Line

The Biceps Femoris (BF) effectively starts the spinal engine. EMG studies have demonstrated that the BF, and the hamstring group as a whole, are active at the end of the swing phase through the early loading of the stance phase of gait. During transition from swing to stance, the Initial Contact (IC) effectively closes the kinetic chain, and the BF can then perform work in a closed chain manner. Within the closed chain, the biceps femoris acts on its more proximal attachment within the chain, the pelvis. The BF attaches to the ischial tuberosity and the sacrotuberous ligament, the SI ligaments, sacrum, sacral fascia, iliac crests, the deep lamina of the TLF, interspinous ligaments and up through the multifidii and lumbar erector spinae

Back Functional Line

At IC, the ipsilateral hip and contralateral shoulder is in flexion; this effectively pre-loads the Back Functional Line, specifically the Gmax and Latissimus Dorsi; this allows for a SSC that provides for extra-spinal propulsion in a 'sling-like' manner; the superficial lamina of the TLF serves as an intermediary between these kinetically linked muscles

Osteoarticuloligamentous Anatomy



Spinal Engine and Anatomy Train Synergy (cont.)

- The Biceps femoris is analogous to the pull cord of the spinal engine by way of inducing a “force closure” of the SI joint, and a subsequent transmission of force up into the osteoarticuloligamentous structures of the lumbosacral spine; and eventually up into the lumbar erector spinae
- The force transmitted through the ligamentous and articular system induces “form closure” of the spinal facet joints and rotation in the lumbar spine; coupled with a lateral flexion moment, the spinal engine ‘gears’ drive the pelvis to rotate forward
- Coincident to the SE rotation and advancement of the pelvis, the AT myofascial meridian effectively lifts and advances the body’s center of mass (COM)
- In terms of the Pendulum theory, The AT function is effectively a slingshot mechanism that engages the spring mass pendulum; effectively increasing gait efficiency
- The anterolateral “serape effect” muscles (IO, EO, TVA) have an antagonistic but synergistic role to the Back Functional Line muscles (Gmax, Latissimus) in producing and controlling torso rotation; they exert their force directly onto the pelvis or onto the TLF via the lateral raphe
- The ‘anatomy train’ contributes contralateral arm swing; this effectively keeps the spinal rotation mechanism contained to the thoracic and lumbopelvic regions; effectively uncoupling the cervical spine and allowing for stabilization of the head

Spinal Engine Counter-rotation

- The induced lumbar rotation effectively stores elastic energy in the spinal ligaments and the annulus fibroses of the intervertebral discs
- It is the return of energy that drives gait
- In order to return the energy the spine must be stabilized from above
- This is accomplished via contralateral arm swing and torso rotation obtained from the contralateral Gmax & Latissimus involvement
- The coupling patterns of the spine has evolved to facilitate the return of this force
- The counter rotation is obtained from the spine and not from the legs

- *Consider the biomechanical effect of inadequate arm swing, poor spinal mobility, poor hip mobility, degenerative disc disease or disc/ligament injury*

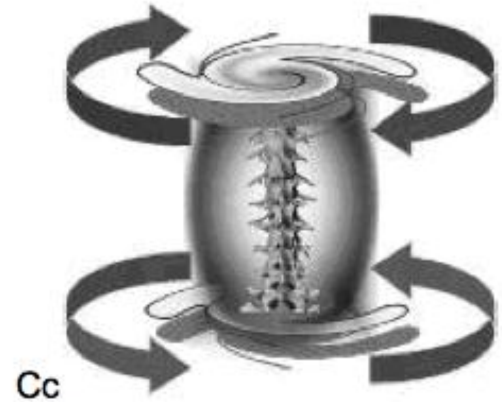


Fig. 3B) Since the legs do not apply a counter-torque to the ground, then the counter-torque must be provided by the structures above the pelvis.

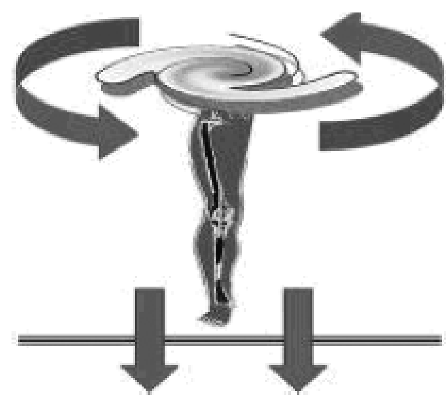
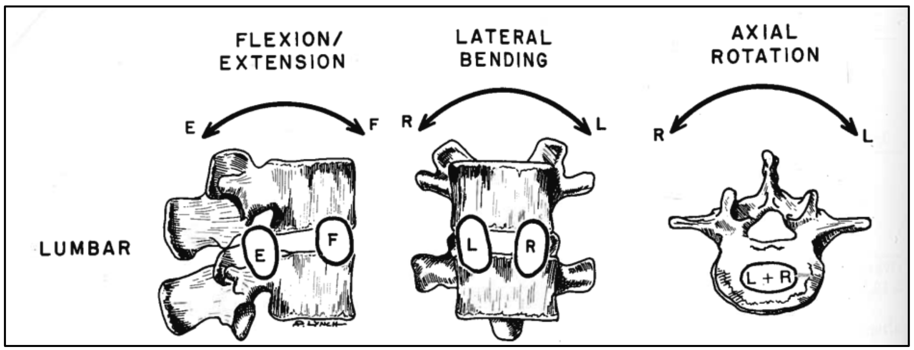
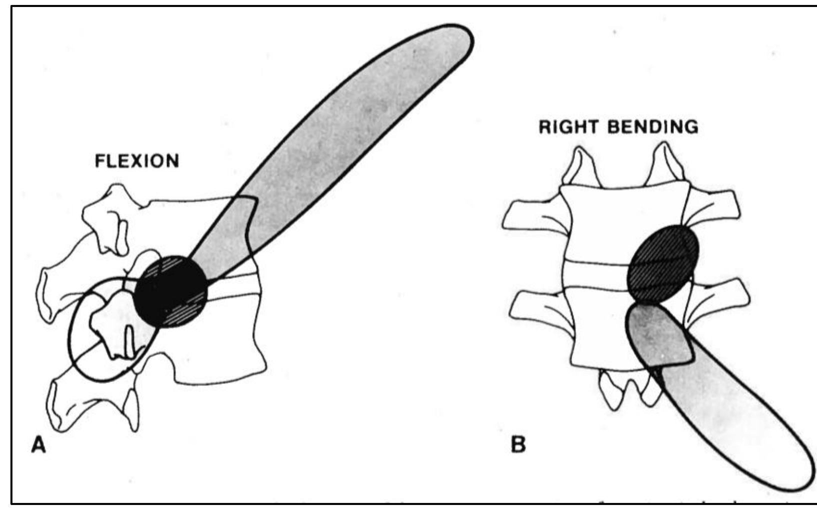


Fig. 3A) If the leg were to apply a torque to the pelvis, then the leg must apply a counter-torque to the ground. That counter-torque is simply not there.

Spinal Mobility



Normal IAR



Pathologic IAR

Spinal Intrinsic Muscle Function

- The spinal intrinsics (rotatores, intertransversii, interspinalii) are not primarily force generators
- Biomechanically they are designed with a small PCSA, and very short moment arms; energetically they will be primarily type 1 muscle fibers
- They are ladened with muscle spindles for proprioception therefore respond to loading/tension
- When loaded these muscles will produce a proportionate amount of strength, but more importantly will recruit higher order musculature (E.S., IO, EO, TVA, etc.) for greater force production and spinal movement or stabilization
- These muscles need stimulus, or they will atrophy as will any muscle
- Atrophied or inhibited intrinsics effectively takes the brains out of the lumbar spine and increases the risk of injury
- Competent SE rotation, lateral flexion and circumduction will load and train these muscles, maintaining their neurological competence

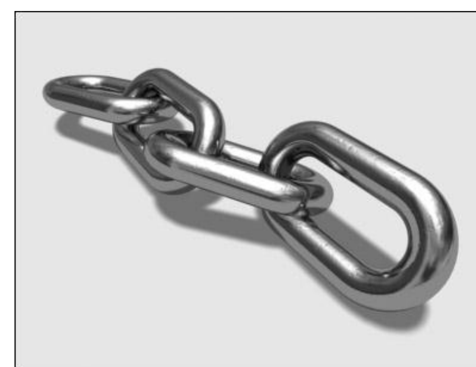
Consider the functional and/or performance effect of a disengaged spinal engine, IVD degeneration, osteoarthritis, segmental restriction, and lumbopelvic dyskinesia

Opened, Closed, & Floating Kinetic Chains

- During normal bi-pedal gait, the upper body and upper extremities serve two vital roles.
  - Provide counter-torque to the lumbar spine to assist in driving spinal rotation and the spinal engine
  - Provide a lift and forward propulsion of the body's center of mass via the "floating kinetic chain" action of the latissimus dorsi and the closed kinetic chain action of the contralateral gluteus maximus.

  - These two muscles are considered to be components of the "Back Functional Line" (Myers), and their action effectively elevates potential energy in the gravitational field; the latissimus dorsi exerts force onto the forward swinging mass of the arm; the momentum (MV) of the arm provides a degree of external load onto which the latissimus exerts its force, effectively getting both an open & closed chain effect; including lifting the pelvis and lumbar spine towards the shoulder and extension of the shoulder to induce the counter rotation needed for the spinal engine

    - *"moment by moment metronome of winding and unwinding"* (Myers)
    - "*spinal motion is repeated at each step, as the spine resonates in the field of gravity*" (Gracovetsky)
    - As the COM is resonating or oscillating in the gravitational field, the spine itself is effectively resonating through the transverse & frontal planes, through periods of winding and unwinding



- The "floating chain" refers to an alternative method of classifying exercises based on mechanics, as proposed by Dillman et al. (1994).
  - Movable Boundary with External Load (MEL) – "floating chain"
  - Fixed boundary with external load (FEL) – classic "closed chain"
  - Movable boundary with no external load (MNL) – classic "open chain"

Why the Legs?

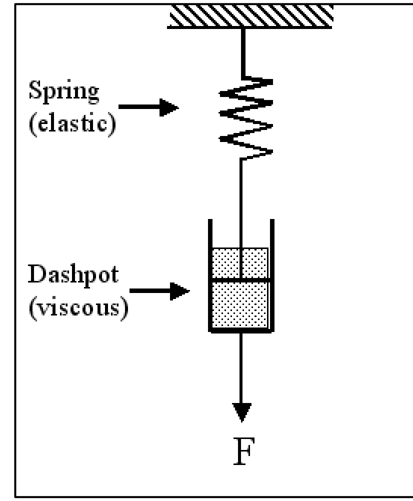
- If the spinal engine mechanism is self sufficient to the degree that we can walk on our ischial tuberosities, what role do legs serve?
  - Conversion of ground reactive forces (GRF) into JRF torques
  - A lever through which to place a torque onto the osteoarticuloligamentous structures of the lumbar spine
  - De facto in-series dampers that provide for attenuation and synching of GRF to the rate and amplitude required by the Spinal Engine
  - Sites of attachment for additional muscle mass; ultimately to provide additional propulsive force generation (i.e. hip, knee and ankle extension)
  - Serve as a lever through which to impart a thrust to the ground
  - Ultimately, to increase the speed of locomotion

Legs Must Mean Something

Secretariat

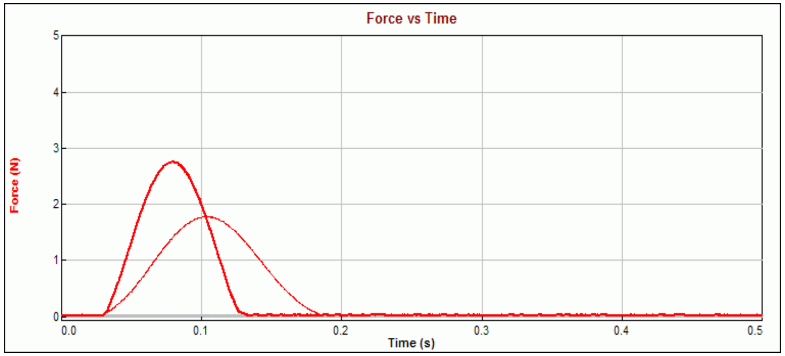
Usain Bolt

In-series Dampers

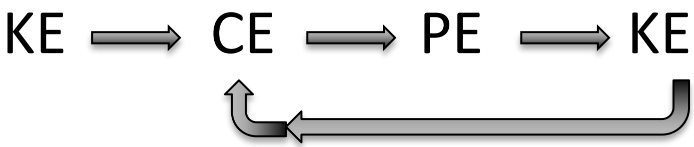


- In mechanical terms a *damper* is a device that deadens, restrains or depresses; a *dashpot* is a damper that cushions, dampens or reverses the motion of a piece of machinery
- The concept of 'tensegrity' suggests that the human torso is not simply analogous to a mass perched upon two boney pillars; rather the musculoskeletal system employs continuous tension and discontinuous compression onto its tissues in such a way that each member operates with the maximum efficiency and economy.
- Given the mass of the torso, head and upper extremities, and given the relative length of the legs, if the human body acted in a 'pillar' fashion as opposed to one of tensegrity, Newton's Laws of physics would predict a high probability of human legs collapsing under its own body weight
- The articulations and connective tissues, along with the leg musculature must continually minimize the compressive forces that are acting through the legs; these structures function to dampen GRFs, and re-calibrate the rate of loading of the GRFs as propagated JRFs so that the passive, viscoelastic structures of the lumbopelvic spine are loaded with an appropriate rate, amplitude and magnitude; and so these kinetic forces are stored as potential energy

In-series Dampers (cont.)



- A mechanical damper, dashpot or shock absorber functions to dissipate kinetic energy; it prolongs the duration over which the force acts, effectively minimizing peak forces
- A 'tuned mass damper' is a device used in automobiles and buildings that functions as a 'harmonic absorber'; this device reduces amplitude of mechanical vibration to prevent discomfort/damage/structural failure
- Human 'in-series dampers' function in this role. Through pronatory articular motions and eccentric muscle control of the lower extremity, kinetic energy is cyclically dampened, converted to potential energy and stored for later use. Energy is conserved and recycled, contributing to an efficient biomechanical machine.



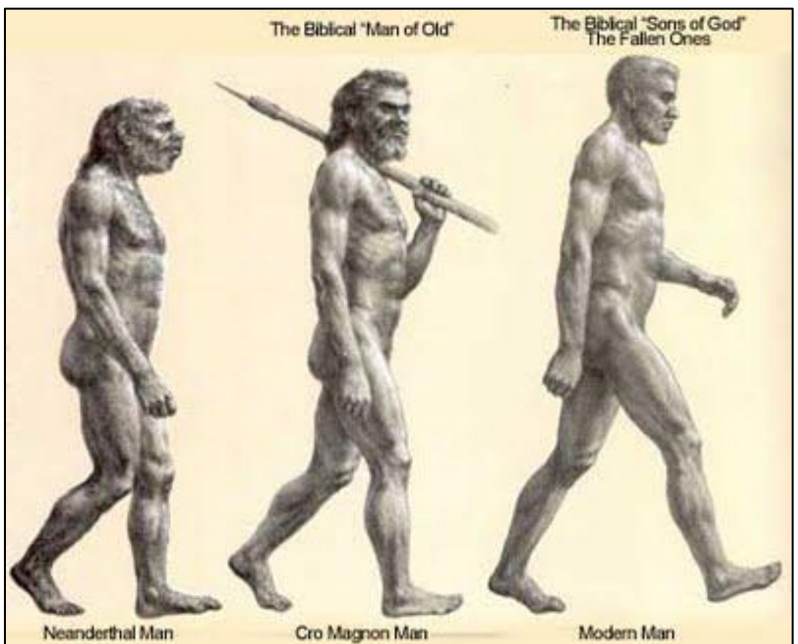
Lumbar Lordosis and the Fate of the Neanderthal? ; a *Very Brief* History of Time

- Between 500-800,000 years ago, a split from a common ancestor eventually lead to the distinctly separate modern Homo Sapien and the Neanderthal “sister species”
- The Neanderthal species came into existence approximately 350,000 years ago; modern man (Homo Sapien) approximately 200,000 years ago.
- During the period from 30,000 - 48,000 years ago, Homo sapiens, Neanderthals and possibly a third species co-existed, could have met and interacted in southern Siberia.
- The Neanderthal demonstrated a significantly more shallow lumbar lordosis than Homo Sapiens; argument has been made that low lordotic angles may have influenced the "shock absorbing" abilities of the Neanderthal spine while increasing stability for things like carrying.*; there may be evidence that Neanderthals exhibited different gait patterns and behaviors from modern humans, for example, being perhaps more efficient when moving on sloped terrains although exhibiting a less economical running gait*
- The Neanderthal species died out approximately 25,000 years ago; hypothetically attributed to a complex mix of climatic change, increased competition with modern humans moving into their ranges, and some small (but significant) degree of interbreeding with modern humans, as evidenced by the Neanderthal genome work that has come out in the last few years.*
- Approximately 12,000 years ago, Homo Floresiensis species died out, leaving Homo Sapien as the sole remaining species from the Genus Homo
- Many Homo species throughout time exhibited bi-pedalism, including Australopithecus as far back as 3.6 million years ago; with evidence of full bi-pedalism by 3 million years ago; Homo Habilis and Homo Erectus were bi-pedal and co-existed 2.5 million years ago (and fashioned the 1st stone tools)
- Modern Humans share 99% of their DNA with Neanderthals; 95-99% with chimpanzees
- Neanderthal relative hypolordosis could be somewhat indicative of differences in activity patterns as compared to Homo Sapien.*

* *Information obtained via personal communication with Eric R. Castillo; PhD Student; Harvard University; Department of Human Evolutionary Biology*

So the loaded question is….

- Did the Neanderthals' shallow lumbar lordosis and spinal biomechanics contribute to their demise?
- A shallow lordosis would have impeded the Neanderthal's spinal engine and its pelvic drive, and ultimately their mobility
- Coupled with other morphological constraints, the Neanderthal was better suited to carry heavy things than he was to ambulate efficiently



Comparative Hominid Lordosis

- ***Lumbar lordosis of Extinct Hominins; Am J Physi Anthropology 147:64-77, 2012***
- The lordotic angles of australopithecines (41 +/- 4) and fossil homo sapiens (54 +/- 14) are similar to those of modern humans (45-65). This analysis confirms the assumption that human-like lordotic curvature was a morphological change that took place during the acquisition of erect posture and bipedalism as the habitual form of locomotion.
- Neanderthals demonstrated markedly smaller lordotic angles (29 +/-4) than modern humans, but higher angles than non-human apes (22 +/-3)
- Non-human apes are not committed bi-peds; when apes ambulate bi-pedally, their gait looks striking similar to hypolordotic humans, i.e. post-surgical patients and young children as they are learning to walk and are simultaneously developing their secondary spinal curvatures

Hypolordotic Human Gait

- ***Characterization of Gait Function in Patients With Postsurgical Sagittal (Flatback) Deformity; Spine 27 (21): 2328-2337, 2002***
- Loss of lumbar lordosis causes anterior displacement of the center of gravity, which creates instability and increases the work of gait; gait deviations result
- Deviations witnessed included shorter steps, decreased stride length and velocity to almost 60% of controls; Step width increased, swing phase duration decreased and double support time increased; Stance duration was prolonged with increased hip and knee flexion during stance. Hip and knee extensor moments were decreased with vertical ground reaction force showing slower rate of loading; reduced peak values and flattening of normal loading response
- These gait deviations compromise the stability of gait and taxes the knee and hip joints adversely.
- Lumbar lordosis range of normal for this study was referenced at 45-65

Evolution of the GMax

The human gluteus maximus and its role in running
Lieberman, Raichlen, Pontzer, Bramble and Cutright-Smith
The Journal of Experimental Biology 209, 2143-2155 Published by The Company of Biologists 2006 doi:10.1242/jeb.02255

- The human gluteus maximus is a distinctive muscle in terms of size, anatomy and function compared to apes and other non-human primates.
- Gmax is in large part electrically silent during low levels of activity, including level and uphill walking
- Gmax activity and timing increase significantly during running.
- The major functions of the gluteus maximus during running are to control flexion of the trunk on the stance leg and to decelerate the swing leg
- contractions of the stance-side gluteus maximus may also help to control flexion of the hip and to extend the thigh.
- Evidence for when the gluteus maximus became enlarged in human evolution is equivocal,
- Gmax's minimal functional role during walking suggests that it was likely important in the evolution of hominid running capabilities.

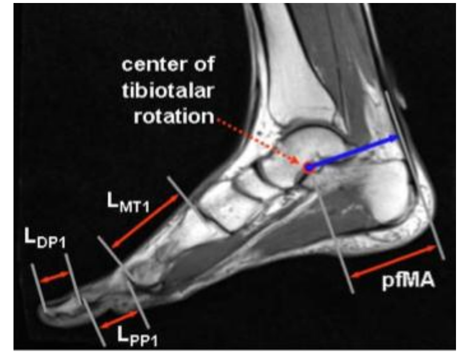
Neanderthal vs Man

Calcaneus length determines running economy: Implications for endurance running performance in modern humans and Neandertals
J Hum Evol. 2011 Mar;60(3):299-308. Epub 2011 Jan 26.

- Running economy (the energy cost of running at a given speed) is strongly related to additional anatomic variables
- The length of the Achilles tendon moment arm can directly impact running economy. Shorter moment arms allow for greater storage and release of elastic strain energy. Greater elastic contribution reduces the required muscle work and therefore reduces energy costs (improves economy).
- In this study, the achilles tendon moment arm length was estimated, based on the length of the calcaneal tuber
- This study did not show a correlation between calcaneal tuber length and walking economy, but it did show a significant correlation with running economy and explains a high proportion of the variance (80%) in cost between individuals.
- Neandertals were found to have longer calcaneal tubers than modern humans; longer tubers would imply greater achilles tendon moment arms, which would decrease the elastic strain energy and increase the muscular effort of running, decreasing economy.
- Calcaneal tuber lengths in early Homo sapiens do not significantly differ from those of present day humans ; this would suggest that the Neandertal running economy was reduced relative to the contemporaneous Homo Sapiens and modern day Homo Sapiens.
- DNA sequencing (Genome Project) has determined that there are Neanderthal genetic relics in modern humans

Foot & Ankle Structure and Running

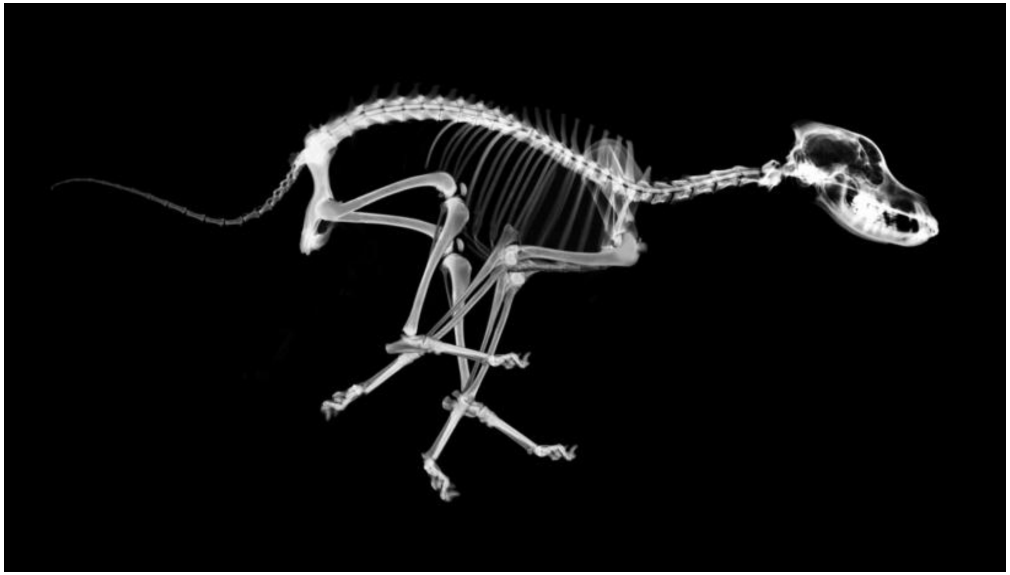
HUMAN SPRINTERS HAVE LONGER FOREFEET AND SHORTER PLANTARFLEXOR MOMENT ARMS
Baxter, Novack, Pennell, and Piazza
American Society of Biomechanics Conference 2011



- The structure of the foot and ankle in sprinters differs from that of non-sprinters. Shorter pfMA coupled with a longer forefoot provides sprinters with a higher ‘gear ratio’ that is likely to provide sprinters with enhanced force generation and longer time of contact that may benefit sprint performance during rapid acceleration.
- This ratio of the GRF moment arm : pfMA is analogous to a “gear ratio” and enables the plantarflexors to operate at a lower shortening velocity and thus maintain muscle force production near toe-off
- The forward impulse that determines this acceleration depends on large forward-directed contact force and contact time sufficient for that force to act.
- The best animal sprinters have limb structures that are favorable for generating large forward impulses.
- Like sprinters, the cheetah has longer toes and metatarsals and a shorter pfMA as compared to less capable sprinters of similar size

NOTE: you cannot coach length, but you can coach technique and you can train for elasticity and force production

Unconscious Competence



Foot & Ankle Morphology in Sprinters

Built for speed: musculoskeletal structure and sprinting ability
Lee and Piazza
Journal of Experimental Biology *November 15, 2009 J Exp Biol 212, 3700-3707*

- Human sprinters’ moment arms estimated from Achilles tendon excursion were significantly smaller than those of height-matched non-sprinters
- The degree to which the measured tendon excursion affected by differences in tendon compliance between the two groups is unclear.

Morphology & Running Abstracts

Ankle joint mechanics and foot proportions differ between human sprinters and non-sprinters (Baxter, Novack Van Werkhoven, Pennell, Piazza)

Proc Biol Sci. 2012 May 22;279(1735):2018-24. Epub 2011 Dec 21.

- Trained sprinters have shorter plantarflexor moment arms and longer forefoot bones than non-sprinters.
- Increasing the ratio of forefoot to rearfoot length permits more plantarflexor muscle work during plantarflexion that occurs at rates expected during the acceleration phase following the sprint start.

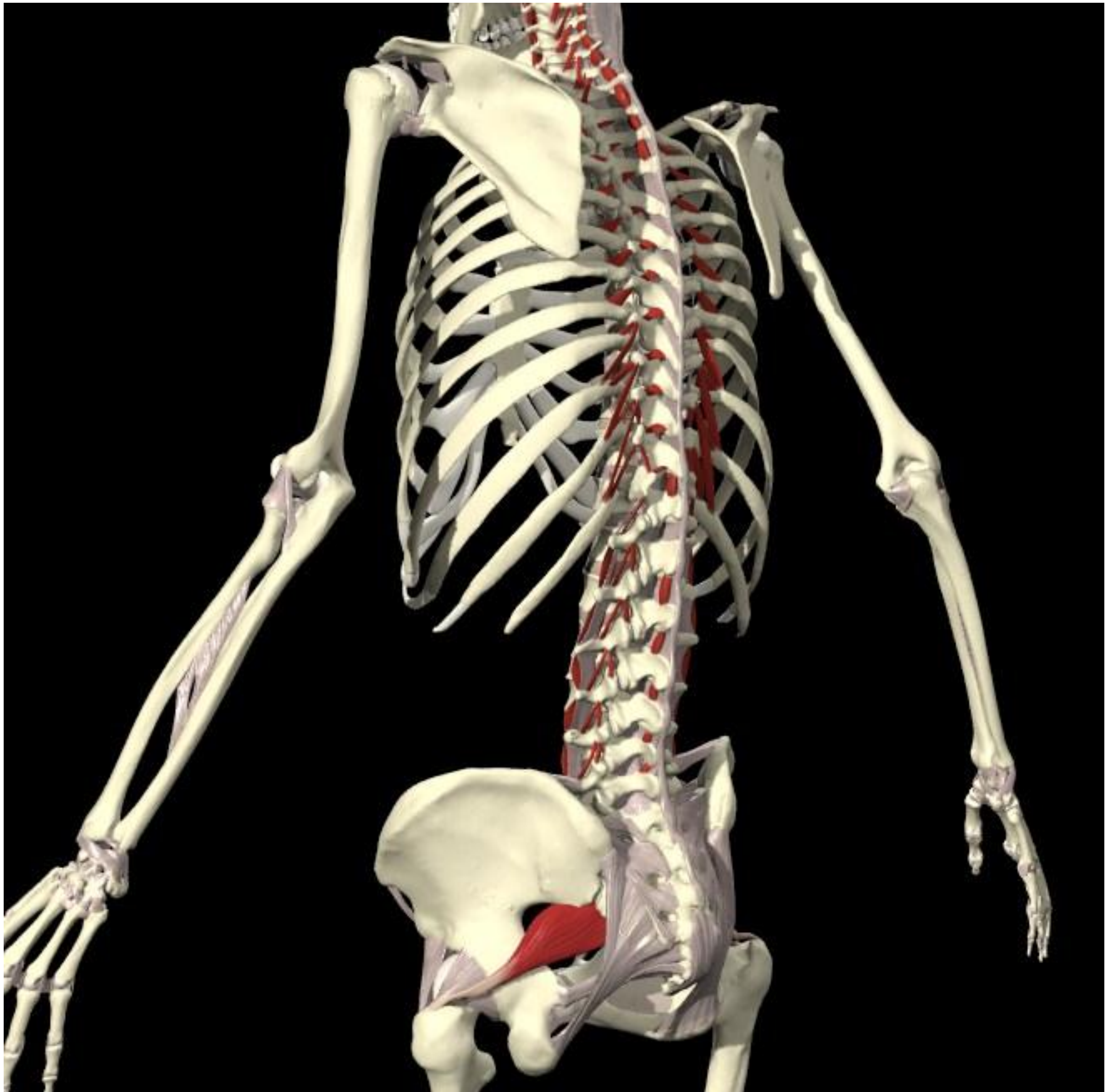
Running biomechanics: shorter heels, better economy

Scholz, Bobbert, van Soest, Clark, van Heerden

The Journal of Experimental Biology 211, 3266-3271

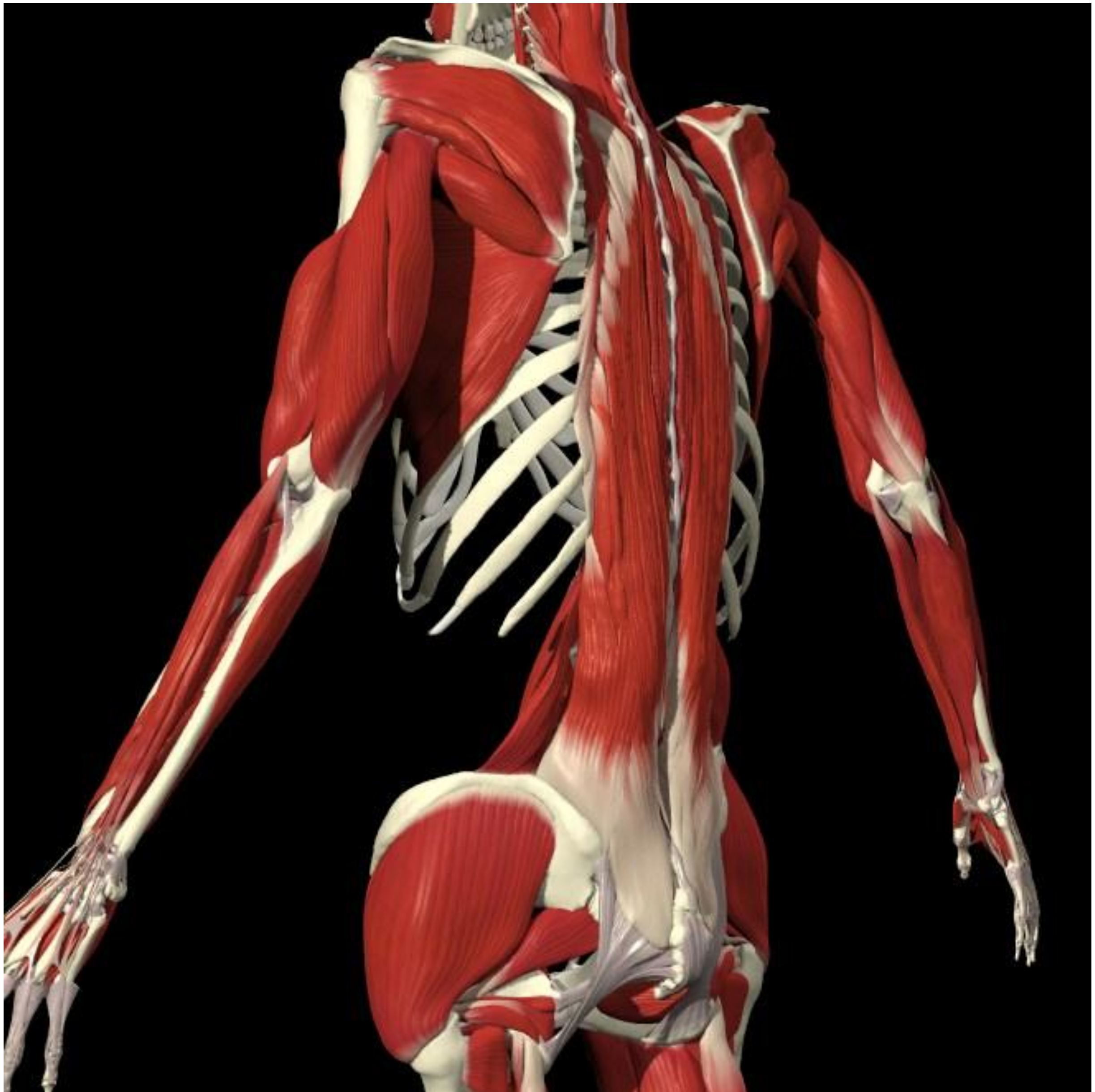
- This study has established a causal relationship between the variation in running economy and the moment arm of the Achilles tendon. Smaller moment arms are associated with better running economy. This relationship was predicted based on a simple musculoskeletal model of tendon energy storage and was confirmed experimentally.

Intrinsic Spinal Musculature

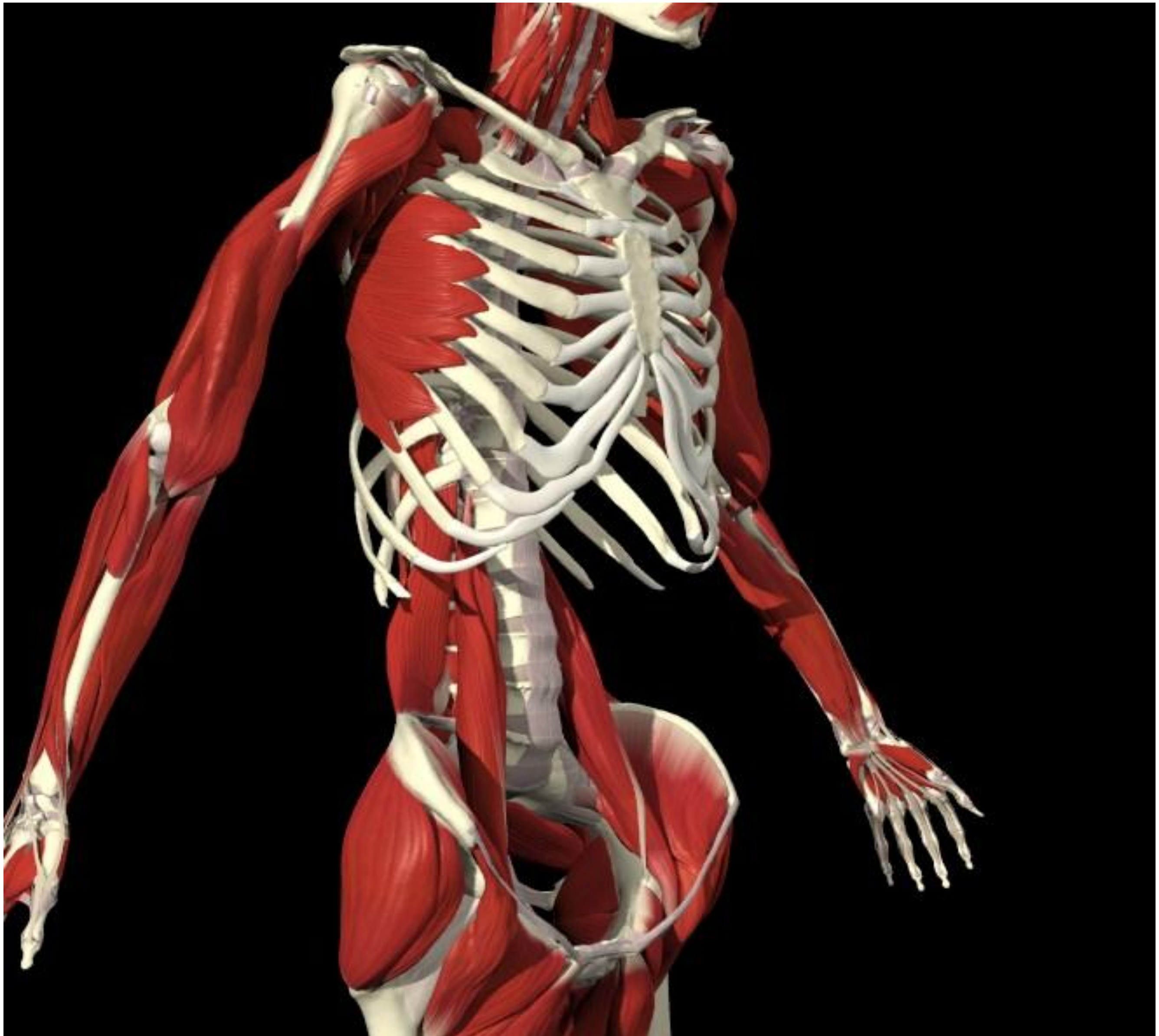


Intrinsic Spinal Musculature (cont.)

Extrinsic Spinal Musculature

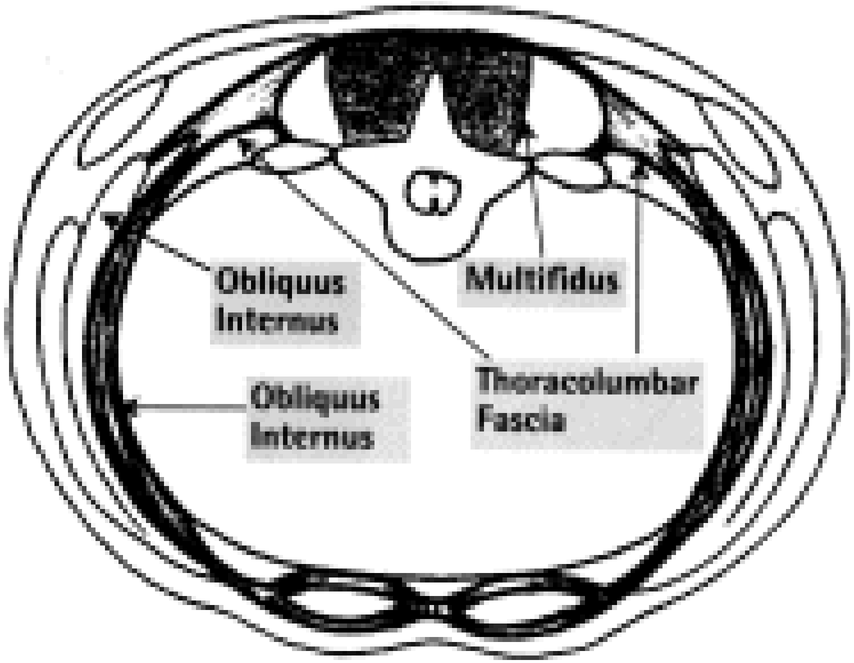


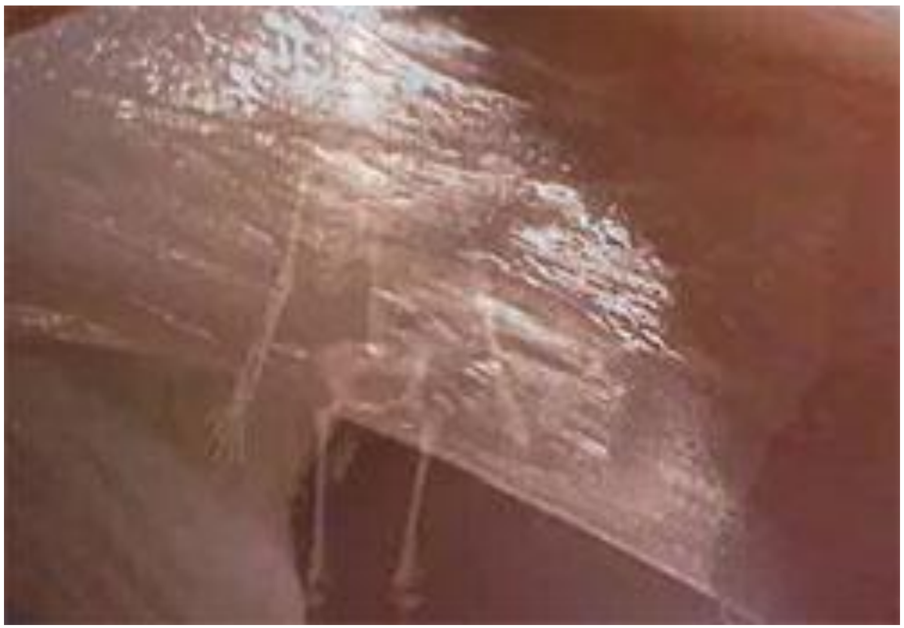
Extrinsic Spinal Stabilizers (cont.)



Extrinsic Spinal Musculature (cont.)

Thoracolumbar Fascia



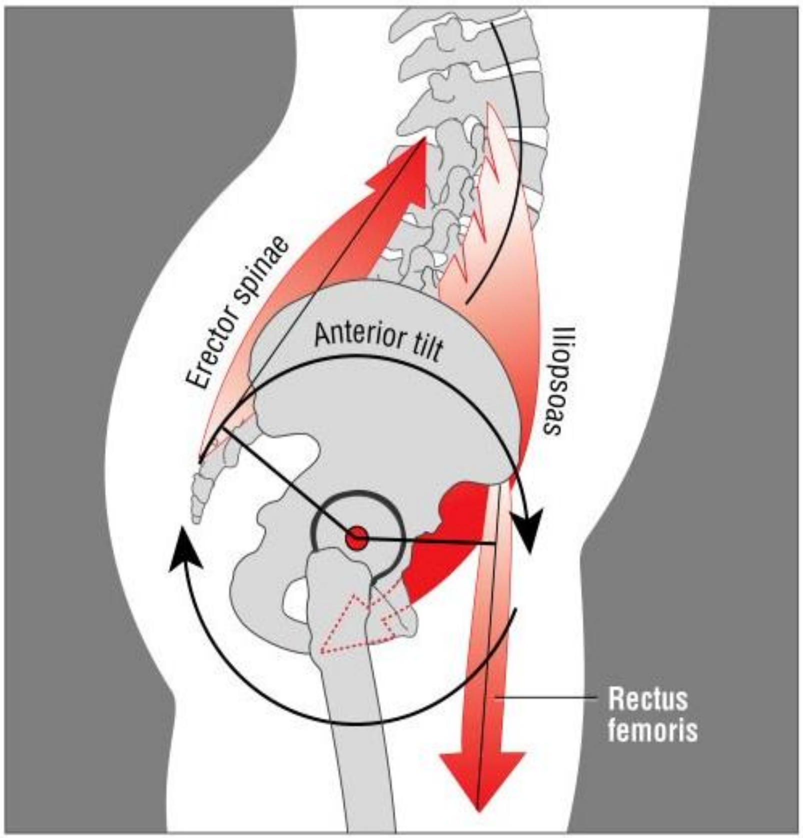


Lumbopelvic Rhythms

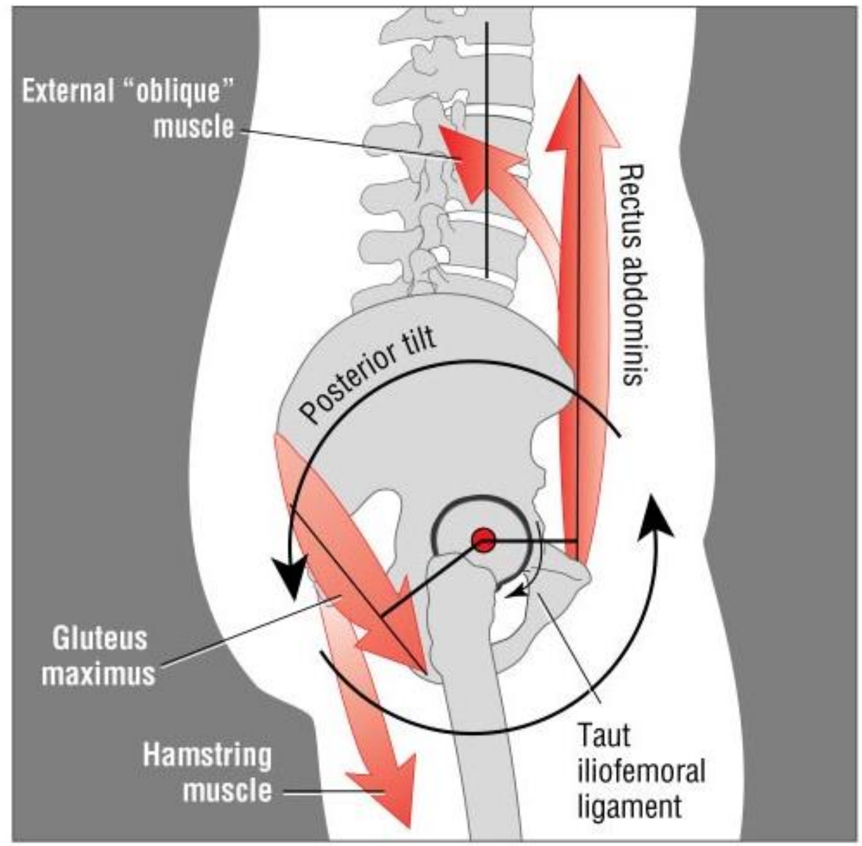
- LPR – the kinematic relationship between the lumbar spine and hip joints during sagittal plane movement
- Ipsi-directional LPR – when pelvis and lumbar spine move in same direction; useful for activities such as extending the reaching capacity of the upper extremities; allows for hip & spinal combined mobility
- Contra-directional LPR – when the pelvis and the lumbar spine move in opposite directions; seen in walking, dancing, or any other activity in which the position of the supralumbar trunk must be held fixed; CDLP rhythms couple hip and lumbopelvic mobility with spinal stability

Contra-Directional Lumbopelvic Rhythm

Pelvic Tilt

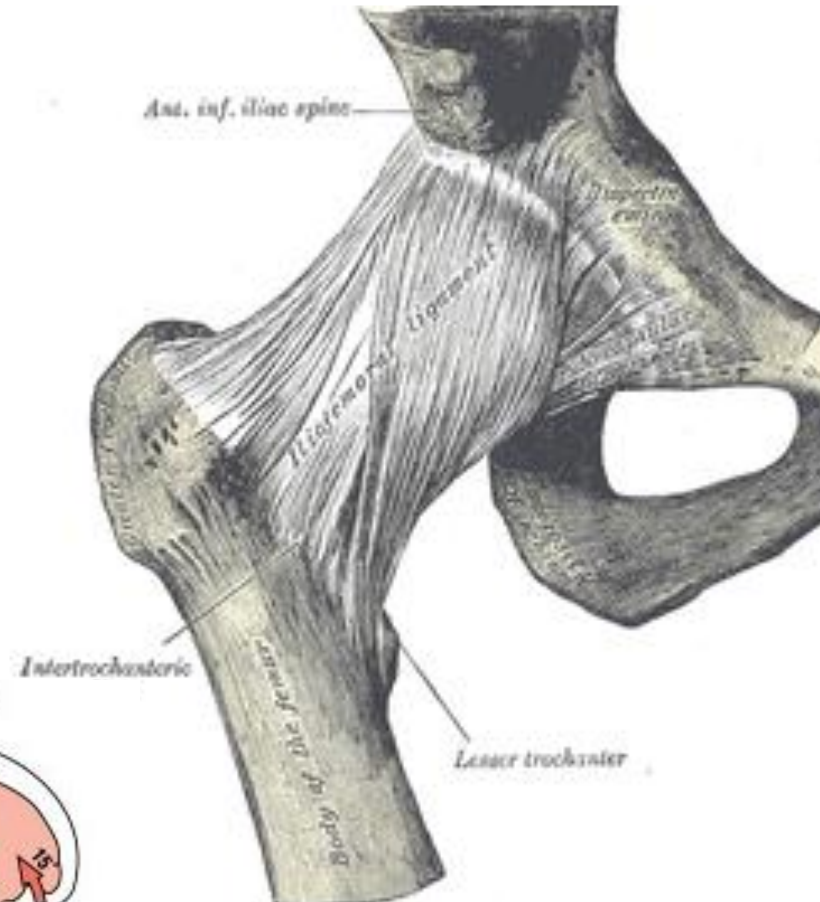


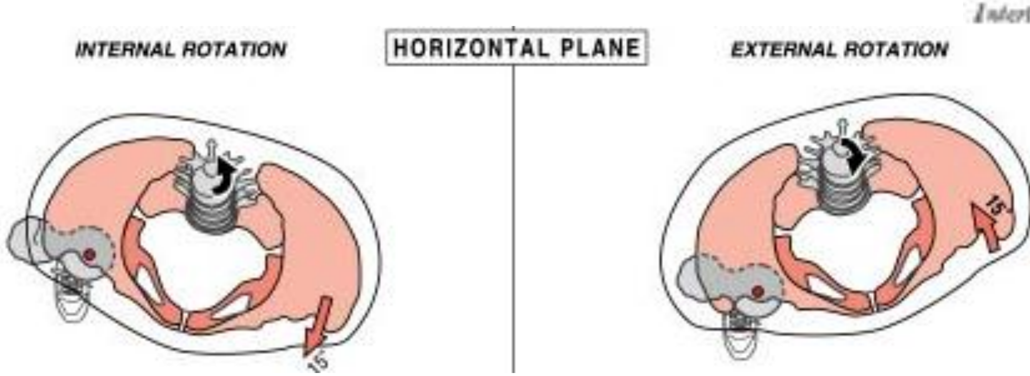
Anterior



Posterior

Hip Mobility & Capsular Patterns

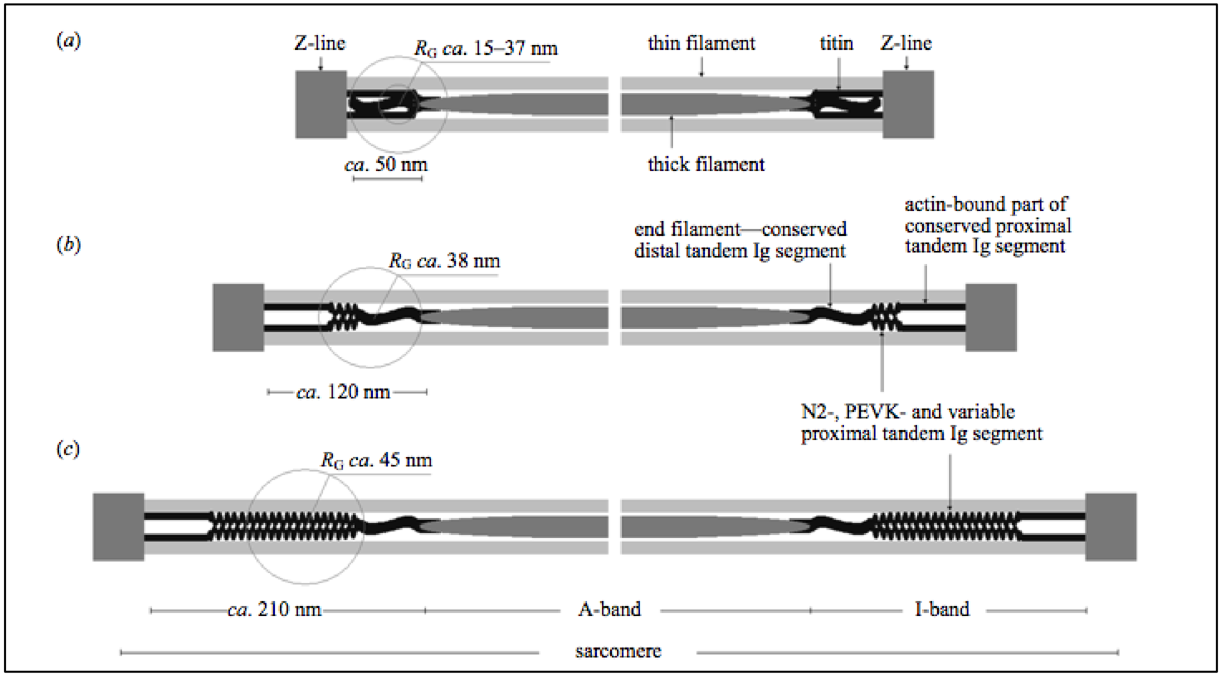


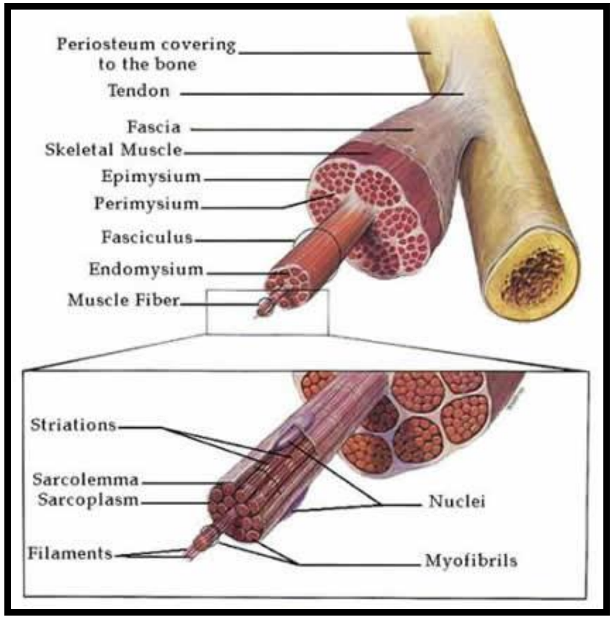


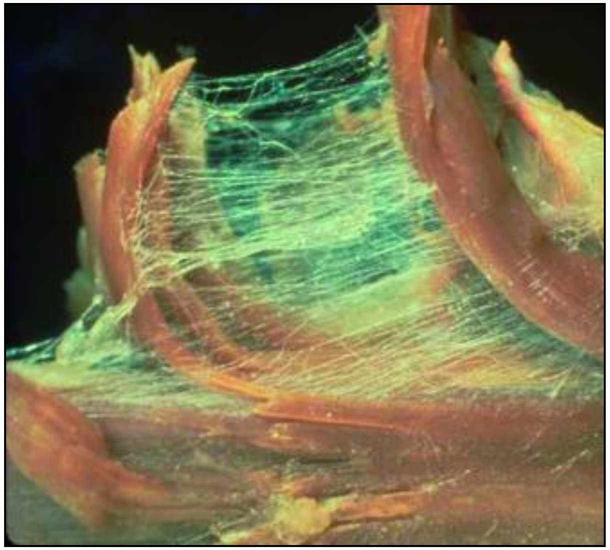
Trendelenburg Sign

The Trendelenburg gait classically represents a pathological gait, most commonly attributed to poor pelvic stabilization in the frontal plane owing to a functional deficit of the stance limb hip abductor group; it can also be viewed as a failure of the frontal plane CDLP

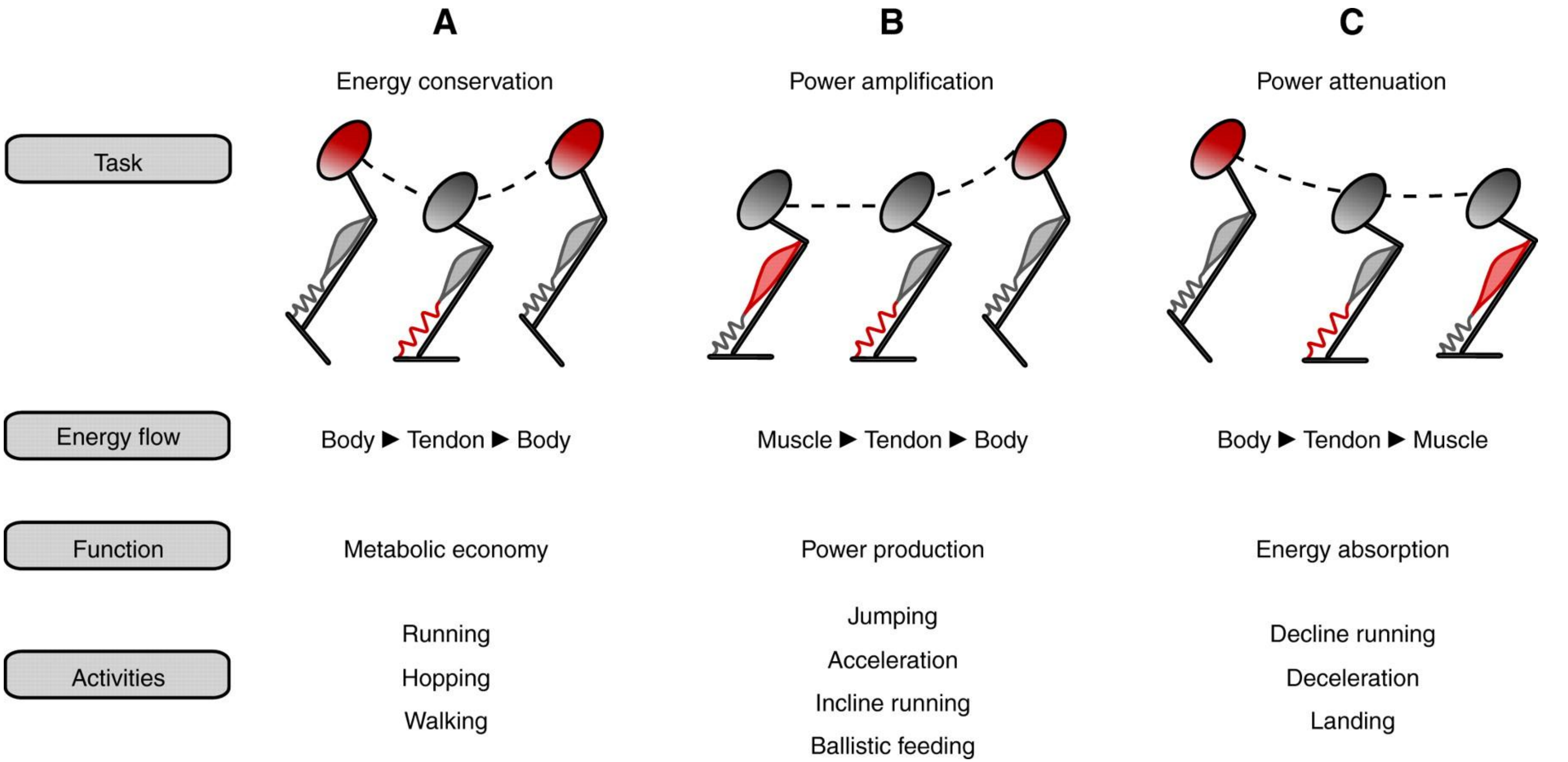
Elasticity & Passive Force Generation







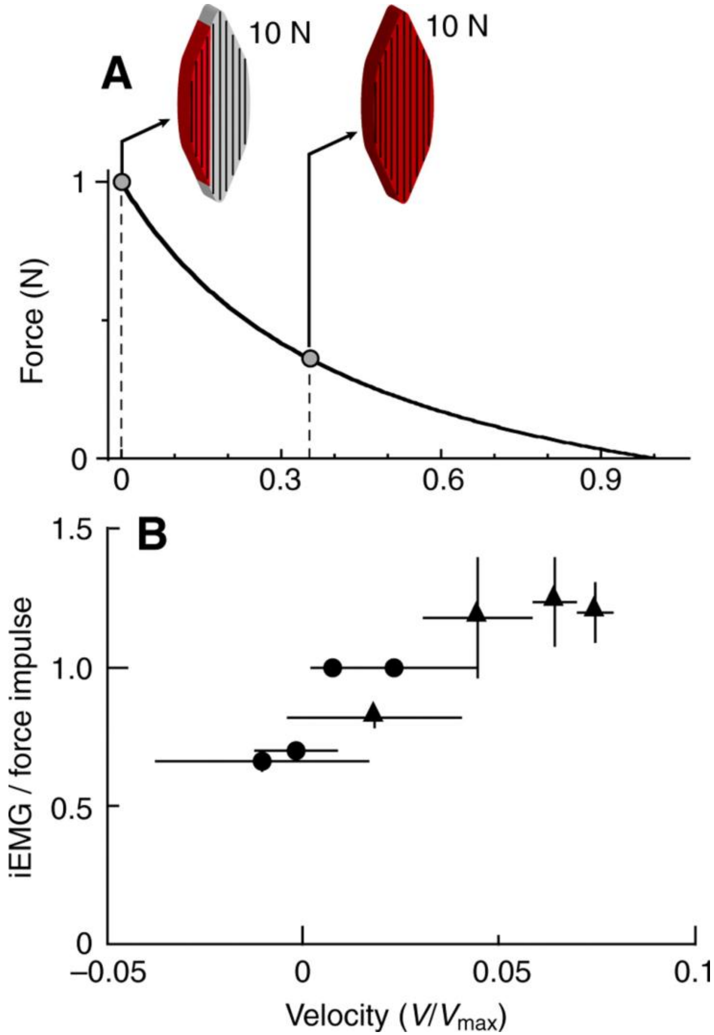
A schematic illustrating how the directional flow of energy in muscle–tendon systems determines mechanical function.



Roberts T J , Azizi E J Exp Biol 2011;214:353-361

The Journal of Experimental Biology

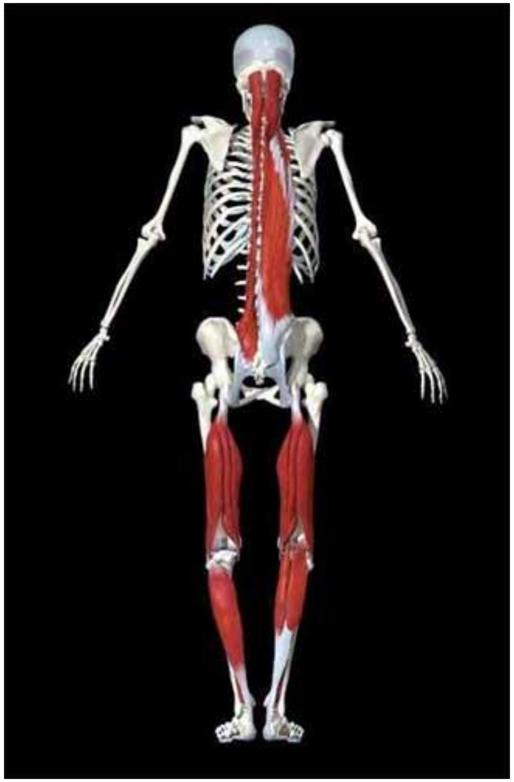
Tendons can reduce the metabolic cost of muscle activity during running by reducing the volume of muscle that must be active to produce force.



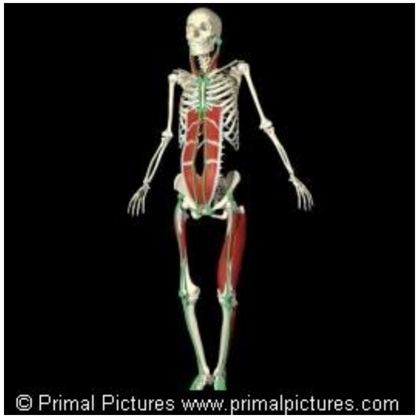
Roberts T J , Azizi E J Exp Biol 2011;214:353-361

The Journal of Experimental Biology

Anatomy Trains



"Anatomy Trains" is a theoretical model of interaction between the muscular and fascial structures throughout the body. This functional approach identifies the synergistic relationships between structures that have been classically categorized as separate entities.



Anatomy Trains and Bi-pedal Gait

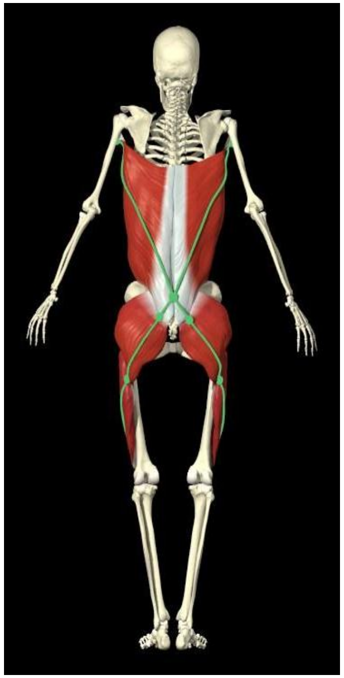
Dr. Rolf in her book "Rolfing" explained: *"Fascial web connects and communicates throughout the body; thickened areas transmit strain in many directions and make their influence felt at distant points, much as a snag in a sweater distorts the entire sweater. This is probably the mechanism through which reflex or pressure points become manifest."*

Bipedal gait involves several fascial ‘trains’ or kinetically and fascially linked muscle groups including the Deep Front Line (DFL), Superficial Front Line (SFL), Superficial Back Line (SBL), Lateral Lines (LL), Spiral Lines (SL), and the arm lines (DFAL, SFAL, DBAL, SBAL).

These fascial lines give rise to the Functional Lines (FFL, BFL), which are named as such based on their kinesiological role, rather than strictly on fascial anatomy. Knowledge of the underlying fascial lines allows for a greater understanding of how the FLs participate in bi-pedal gait.

Extending distally from the functional lines are the Arm Lines (FFL, BFL). The arm lines have an obvious fascial and functional connections with the LLs, SLs, and FLs.

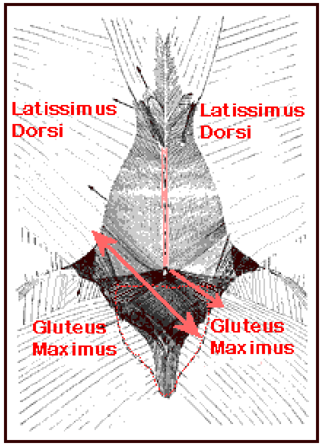
Anatomy Trains – Functional Lines & Bi-Pedal Gait



The Functional Lines – these lines are termed as such because they represent a functional collaboration between two or more fascial lines; therefore they are not continuous lines, but work in kinetic synergy

- Front Functional Line (FFL) – kinetic linkage running from the upper portion of the humerus, along the anterior portion of the ribcage, to the ipsi-lateral pubic bone and pubic symphysis; the non-fascial, kinetic linkage then continues from the contralateral pubic bone to the posterior aspect of the mid-femoral shaft. The FFL passes through the lower division of the pectoralis major, the lateral division of the rectus abdominus, the abdominal aponeurosis, the upper division of the external oblique, and finally, the adductor longus.

- Back Functional Lines (BFL) – kinetic linkage running from the upper portion of the humerus, to the sacrum, femur, patella and eventually to the tibial tuberosity. The BFL passes through the latissimus dorsi, thoracolumbar and sacral fascia before it crosses the midline at the lumbosacral junction to the contralateral gluteus maximus, vastus lateralis



Anatomy Train (cont.)

- The extension of the Front Functional Line into the contralateral adductor musculature will be affected by the position of the lower extremity (LE) and the nature of the lower extremity kinetic chain (closed vs. open)
  - with the open chain LE activity during the swing phase of gait, the fascial network of the adductor group (DFL) will passively contribute to force generation from extension into flexion, through the kinetic functional relationship between two separate fascial lines (FFL & DFL). Kicking is another example of this.
  - closed chain LE extension occurring during the stance phase is synergized with contralateral open chain arm swing into extension, effectively tensioning the combination of the DFL, FFL, SL, and by extension the arm lines (AL). This tensioning stores elastic, potential energy in the viscoelastic fascial and muscular connective tissues.
  - With the LE in flexion, contralateral arm swing during gait will also be in flexion. Force generation into this position will be largely through FFL muscular activity, as the elasticity of the fascial systems is negligible.
  - With the transition of the stance leg into extension, the elastic, potential energy that has been stored in the myofascial structures of the BFL can be utilized as kinetic energy to generate LE extension and contralaeral arm extension

Trains or Engines – Velocity Dependent?

The goal of movement, and therefore gait velocity may be the largest determining factor of which system or systems we use for locomotion.

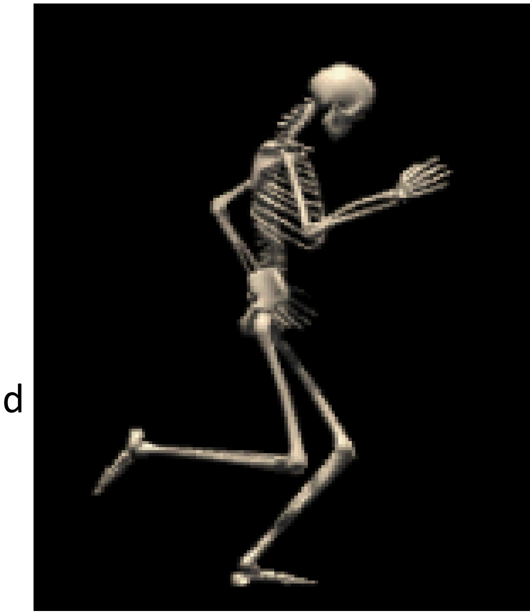
Newton's Law of Acceleration states that acceleration of a body is directly proportional to the force causing the acceleration. With increasing velocity of gait, there is a concomitant rise in force demands, and therefore, greater recruitment and utilization of additional anatomical systems.

The Law of Acceleration also states that acceleration is inversely proportional to the mass of the body. This means that at a given velocity, a heavier individual has to generate more force than a lighter individual to maintain gait velocity, as gait is a series of accelerations and decelerations. This force demand occurs during absorption and propulsion, and can be derived from both passive and active generators.

This increasing force requirement is a contributing factor to the tendency of slower gait in heavier individuals. As total body mass increases, strength to mass ratios decrease. Heavy, de-conditioned individuals (low fat free to total body mass ratio) will rely more on frontal plane shifting of the trunk and momentum for force generation. They will be less likely to utilize their spinal engine or anatomy trains to drive the forces rotationally through their bodies. This is due to many factors, including a natural tendency towards economy and the diminished force capacity relative to their body mass. As body weight is accumulated over time, each and every step serves as a 'learning process' and may have effect on the neuromotor programming

Gait Economy

Biomechanical Efficiency of Gait

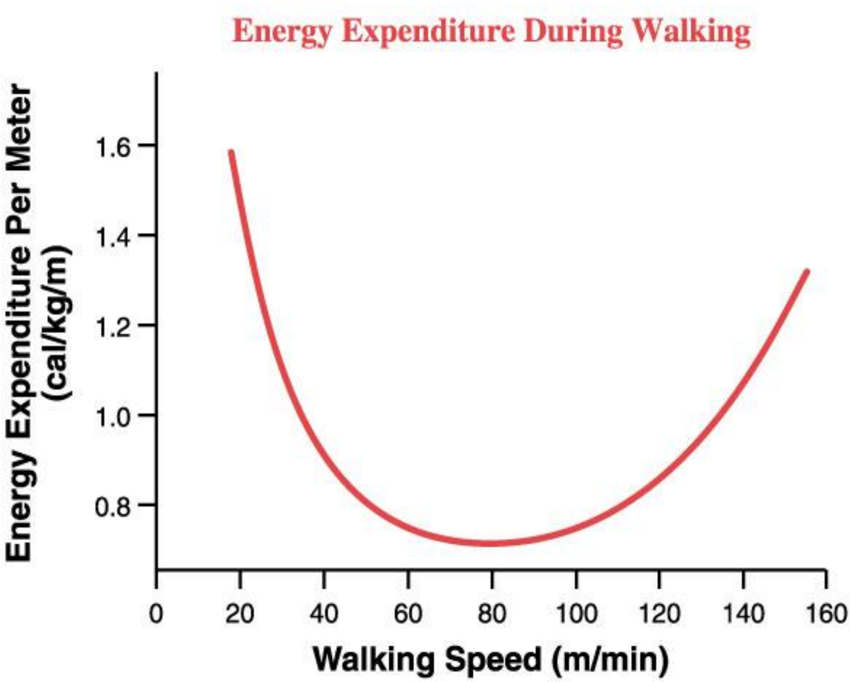


- Greater gait speeds involve greater forces, both into (absorption) and out of (propulsion) the body.
- The efficiency of human gait will be strongly determined by the structural and functional integrity of the biomechanical system. This entails both the active and passive force generation systems.
- At increasing gait speeds, a more mechanically economical and efficient anatomical system will return a larger percentage of the forces that were placed upon it. This efficiency of force return is strongly dependent on the elastic and viscoelastic properties of the system's connective tissues.
- Theoretically, with 100% elastic efficiency, there would be little need for active, muscular force production. Human gait would continue on similar to a rubber ball. In reality, the anatomical system is much less than 100% elastic, therefore needs active force production form the musculature to make up for the loss of elastic energy. The active muscle force production essentially supplements the passive connective tissue force production.
- Biomechanically efficient gait occurs with the synergy between our active and passive force generation systems

Gait Economy

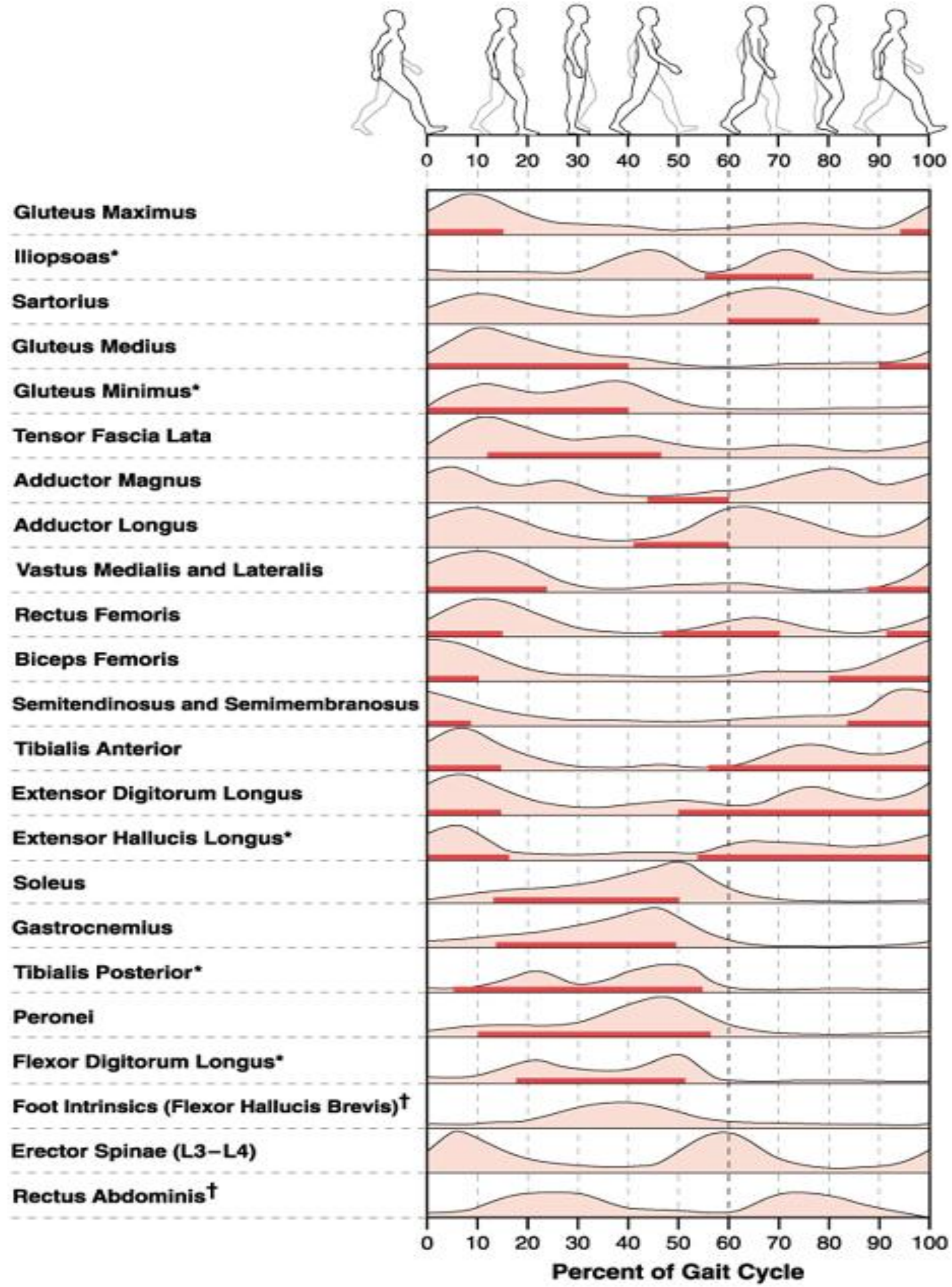
<u>Economy</u> – frugality in the expenditure of resources

<u>Efficiency</u> – the ratio of work done per expenditure of resources

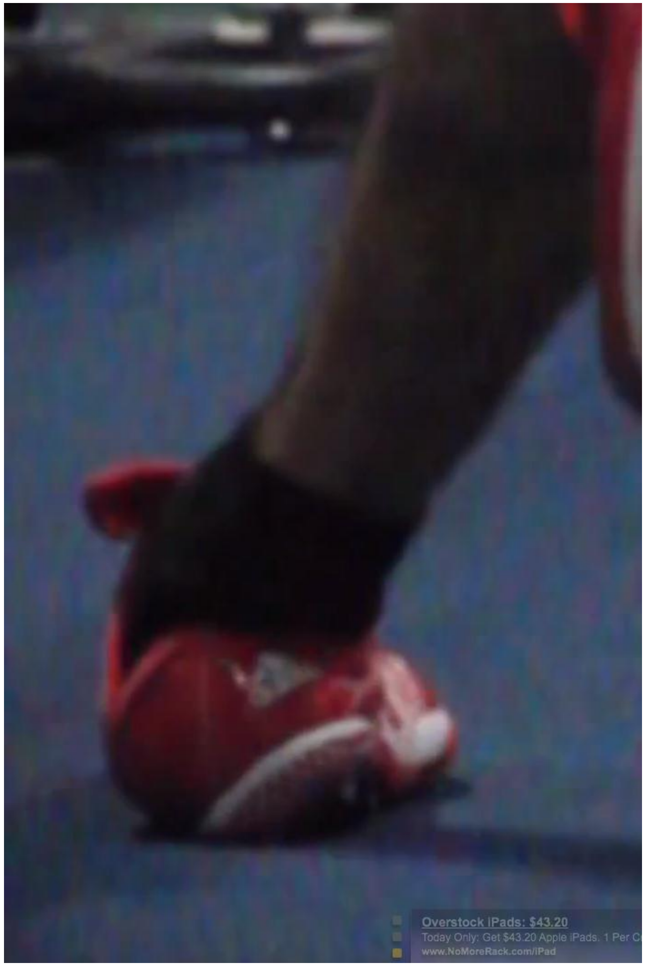


- ❑ Gait economy will occur at a particular speed. This speed is based on many factors, including the biomechanical efficiency of the individual.
- ❑ The body attempts to conserve energy expenditure by minimizing excursion of C of M, controlling body momentum & taking advantage of intersegmental transfers of energy
- ❑ With non-hurried, purposeful gait, individuals will subconsciously select a gait speed that is most economical for them.
- ❑ Typically, human gait is most economical at approximately 80 meters/min, or 3 MPH.
- ❑ This does not imply that the force or caloric demands are less at 3 MPH than they are at 2 MPH, it implies that there is a *lower rate* of caloric expenditure per distance covered.
- ❑ Beyond this 3 MPH mark, the economy of gait lessens, in other words, gets more expensive in terms of caloric expenditure cost.

Timing & Relative Intensity of EMG During Gait



Hope For This



Prepare For This

[2012 NCAA Indoor Track Championships]

Giants

- Serge Gracovetsky, PhD
- Robert Lovett, MD
- The Optimum Spine. Spine. Gracovetsky S, Farfan H. 1986 Jul-Aug;11(6):543-73.
- The mechanism of the lumbar spine. Spine. Gracovetsky S, Farfan H., Lamy C. 1981 May-Jun;6(3):249-62.
- Vleeming A. et al. *Movement, Stability & Low Back Pain*. Churchill Livingstone, 1997

  Contributing authors: C.J. Snijders, A. Vleeming, R. Stoeckart, J. M. A. Mens, G. J. Kleinrensink, V. Mooney, R. Pozos, J. Gulick, D. Swenski, A. Huson, J.P. van Wingerden, C.O. Lovejoy, B. Latimer, R. McNeill Alexander, D. Lee, P.E. Greenman, S.A. Gracovetsky, Levin S.
- White, A.A., Panjabi, M. (1988): *Clinical Biomechanics of the Spine*. Philadelphia, Lippincott.
- Gracovetsky S. (1988): *The Spinal Engine*. Second edition 2008.
- Myers TW, 2001: *Anatomy Trains*. Churchill Livingstone
- McGill S, *Low Back Disorders;* Human Kinetics, 2007
- Gardiner PF, *Advanced Neuromuscular Exercise Physiology*; Human Kinetics, 2011
- Oatis CA; Kinesiology; Lippincott Williams & Wilkins,2009.
- Sahrmann SA; Diagnosis and Treatment of Movement Impairment Syndromes; Mosby 2002
- Neumann, D.A. (2002)*. Kinesiology of the Musculoskeletal System*. St. Louis, Missouri. Mosby.
- Dillman CJ, Murray TA, Hintermeister RA. 1994 Biomechanical Differences of Open and Closed Kinetic Chain Exercises with Respect to the Shoulder. J Sport Rehabil 3:228-238.
- Ellenbecker TS, Davies GJ. 2001*: Closed Kinetic Chain Exercise.* Human Kinetics (p 4-5)
- The Stabilizing System of the Spine. Part I. Function, Dysfunction, Adaptation, and Enhancement. Journal of Spinal Disorders & Techniques. M.M. Panjabi. 1992 (5);4
- *Characterization of Gait Function in Patients With Postsurgical Sagittal (Flatback) Deformity; Spine 27 (21): 2328-2337, 2002*
- Roberts T J , Azizi E J Exp Biol 2011;214:353-361. *Simple spring–mass models can reproduce key features of the dynamics of running and walking.* J of Experimental Biology
- Dickinson, Farley, Full, Koehl, Kram, Department of Integrative Biology, University of California Berkley; *How Animals Move: An Integrative View* 7 April 2000: Vol. 288 no. 5463 pp. 100-106.

More Giants

- D.E. Lieberman, D.A.Raichlen, H.Pontzer, D.M. Bramble and E. Cutright-Smith. The human gluteus maximus and its role in running. The Journal of Experimental Biology 209, 2143-2155
- Gracovetsky, S. (1985): "An Hypothesis for the Role of the Spine in Human Locomotion: A Challenge to Current Thinking". *J Biomed Eng* 7, pp. 205-216.
- Farfan HF, Gracovetsky S. *The Nature of Instability.* Spine (Phila Pa 1976). 1984 Oct;9(7):714-9.
- Baxter, Novack Van Werkhoven, Pennell, Piazza. *Ankle joint mechanics and foot proportions differ between human sprinters and non-sprinters.* Proc Biol Sci. 2012 May 22;279(1735):2018-24. Epub 2011 Dec 21.
- Scholz, Bobbert, van Soest, Clark, van Heerden. *Running biomechanics: shorter heels, better economy.* The Journal of Experimental Biology 211, 3266-3271
- Lee and Piazza. *Built for speed: musculoskeletal structure and sprinting ability.* Journal of Experimental Biology *November 15, 2009 J Exp Biol 212, 3700-3707*
- E. Been, A.Gomez0Olivencia, P. Kramer. *Lumbar Lordosis of Extinct Hominins.* Amer J of Phys Anthropology 2011; 147:64-77
- Baxter, Novack, Pennell, and Piazza. *Human Sprinters Have Longer Forefeet and Shorter Plantarflexor Moment Arms*. American Society of Biomechanics Conference 2011
- *Calcaneus length determines running economy: Implications for endurance running performance in modern humans and Neandertals.* J Hum Evol. 2011 Mar;60(3):299-308. Epub 2011 Jan 26.
- M Goulding. *Circuits controlling vertebrate locomotion: moving in a new direction*. Nat Rev Neurosci. 2009 July; 10(7): 507–518
- Vaughan CL. *Theories of bipedal walking: an odyssey*. Journal of Biomechanics 36 (2003) 513–523
- Morgan DL, Proske U. *Can all residual force enhancement be explained by sarcomere non-uniformities? January 15, 2007 The Journal of Physiology, 578, 613-615.*
- Morgan DL, Proske; *Popping Sarcomere Hypothesis Explains Stretch Induced Muscle Damage;* U*Proceedings of the Australian Physiological and Pharmacological Society (2004)* ***34:*** *19-23*
- Morgan DL. *New insights into the behavior of muscle during active lengthening;* 209 Biophys.J.eBiophysicalSociety; Volume57 February1990 209-221
- K.A.P. Edman. *Residual force enhancement after stretch in striated muscle. A consequence of increased myofilament overlap?* March 15, 2012 The Journal of Physiology, 590, 1339-1345.
- Roberts TJ, Azizi E. *Flexible mechanisms: the diverse roles of biological springs in vertebrate movement.* J Exp Biol. 2011 Feb 1;214(Pt 3):353-61.
- *Gill KP, Callaghan MJ. The measurement of lumbar proprioception in individuals with and without low back pain.* Spine (Phila Pa 1976). 1998 Feb 1;23(3):371-7.
- Maus HM, Lipfert SW, Gross M, Rummel J, Seyfarth A. *Upright human gait did not provide a major mechanical challenge for our ancestors.* Nat Commun. 2010 Sep 7;1:70.

And More Giants

- R McNeill Alexander. *Tendon elasticity and muscle function;* Comparative Biochemistry and Physiology - Part A: Molecular & Integrative Physiology; Volume 133, Issue 4, December 2002, Pages 1001–1011
- Lindstedt, Reich, Keim, LaStayo; *Do muscles function as adaptable locomotor springs?;* The Journal of Experimental Biology 205, 2211–2216 (2002)
- Brockett, Morgan, Proske; *Predicting Hamstring Strain Injury in Elite Athletes;* Medicine & Science in Sports & Exercise: March 2004 - Volume 36 - Issue 3 - pp 379-387
- Brockett, Morgan, Proske; *Human hamstring muscles adapt to eccentric exercise by changing optimum length;* Medicine & Science in Sports & Exercise: May 2001 - Volume 33 - Issue 5 - pp 783-790
- Philippou, Maridaki, Bogdanis, Halapas, Koutsilieris; *Changes in the Mechanical Properties of Human Quadriceps Muscle after Eccentric Exercise; Int J of Exp and Pathophys and Drug Res; September-October 2009 vol. 23 no. 5 859-865*
- Tskhovrebova, Trinick; *Role of titin in vertebrate striated muscle;* Phil. Trans. R. Soc. Lond. B (2002) 357, 199–206
- Minajeva, Kulke, Fernandez, Linke; *Unfolding of Titin Domains Explains the Viscoelastic Behavior of Skeletal Myofibrils*; Biophysical Journal Volume 80 March 2001 1442–1451
- *Lieberman, Bramble; The Evolution of Marathon Running Capabilities in Humans;* Sports Med 2007; 37 (4-5): 288-290
- Lieberman, Bramble, Raichlen, Shea; *The evolution of endurance running and the tyranny of ethnography: A reply to Pickering and Bunn (2007); Science Direct;* Journal of Human Evolution 53 (2007) 434e437
- *Lieberman, Bramble; Endurance running and the evolution of Homo*; Nature Vol 432, NOV 18 2004
- Lieberman DE*; The Rise and Fall of Seasonal Mobility Among Hunter-Gatherers; Current Anthropology, (34) 5, Dec 1993*
- Lieberman, Venkadesan, Werbel, Daoud, D'Andrea, Davis, Mang'Eni, Pitsiladis; *Foot strike patterns and collision forces in habitually barefoot versus shod runners;* Nature. 2010 Jan 28;463(7280):531-5.
- O'Connor, F and Wilder, R (2001). Textbook of Running Medicine, McGraw Hill.
- McGinnis, P.M. (2005). Biomechanics of Sport and Exercise 2nd ed. Champaign, IL. Human Kinetics.
- Cavanagh, P.R. (1990). Biomechanics of Distance Running. Champaign, IL. Human Kinetics
- Primal Pictures; Interactive Functional Anatomy 1st edition

Thanks

- Thank you to:
- Serge Gracovetsky, PhD for his help and contributions
- Eric R. Castillo; PhD Student; Harvard University; Department of Human Evolutionary Biology for his personal communications
- Kim Blair, PhD for his contribution
- Art Horne, ATC for his commitment to the collaborative effort
- John Marchese, DC for his inspirational pursuit of all things therapeutic
- Carl Valle, CSCS for his unrelenting persistence regarding sports performance
- And to the many, many Giants whose work was not cited above

Einstein Genius

- "Great spirits have always found violent opposition from mediocrities. The latter cannot understand it when a man does not thoughtlessly submit to hereditary prejudices but honestly and courageously uses his intelligence.”

- "If we knew what it was we were doing, it would not be called research, would it?”

- "He who joyfully marches in rank and file has already earned my contempt. He has been given a large brain by mistake, since for him the spinal cord would suffice.”

- "Life is like riding a bicycle. To keep your balance you must keep moving.”