Linking the spinal engine with the legs: a theory of human gait

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Chapter 20

LINKING THE SPINAL ENGINE WITH THE LEGS
A Theory of Human Gait

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INTRODUCTION

Human gait is unique from an evolutionary perspective, although the reasons for it and the advantages it brought are still a matter of conjecture. A mechanism to explain how the human spine evolved from our fish ancestors was proposed in 1985. This early theory of the spinal-engine did not describe the specific interactions of the spine with the legs. The purpose of this paper is to review and generalize the theory to merge spine and legs into a single machine, which achieves what is termed human gait.

Lovett (1903) discovered that a lordotic spine, when bent to either side, induced an axial torque, a phenomenon dubbed "coupled motion" and studied in detail by Panjabi and White (1971). Nachemson (1963) analyzed the conditions under which the lumbar disk could be damaged by excessive compression. Farfan (1973) argued that excessive torsion was responsible for disc pathology. Following these leads, a considerable amount of experimental and theoretical work established that disc injury results from a combination of both compression and torsion, with torsion being perhaps the most damaging element. Since lower back injuries are among the non life-threatening diseases representing the greatest burden socially and economically, many were quick to interpret the experimental data to mean that indeed compression and torsion ought to be avoided in the work place. However, administrative guidelines proposed by NIOSH (1981) to take these findings into account did not result in any kind of reduction or slowdown in the incidence of lower back injuries.

And if torsion were indeed the primary source of disc pathology, why did we acquire a spine which allows for high levels of torsion? If so, then the 33 vertebrae prone to disc disease ought to have been replaced through evolution by stronger components. The fact that we did not evolve in such a manner suggests that the high incidence of torsional injury ought to be compensated by some fundamentally important advantage for our species.

It was essential to have access to more precise descriptions of dorsal and sacral musculature in order to relate spinal motion and the motion of the legs. By the early 1980s, Bogduk and Twomey (1987) had refined Gray's description of spinal musculature to a point where it was possible to realistically analyze spinal motion through mathematical modeling. We proposed that the properties of spinal movement ought to be determined by the need to survive, that is, to execute tasks in such a way that the stress within all structures ought to be minimized and equalized. This seemingly broad hypothesis led us to realize that the concept of the spine as a rigid "column" was no longer tenable, and that the human spine not only was capable of torsion and compression, but that these properties of the spine are fundamental to its role in locomotion.

The theory of the "spinal-engine" (Gracovetsky 1988) incorporates these ideas. In essence, we suggested that the evolutionary pressures for efficient locomotion on land forced the spine of our fish ancestors to evolve into our curved spine. The lordotic spine converts the primitive piscine lateral bend into an axial torque driving the pelvis. This theory neatly explained the need for spinal compression and torsion in locomotion. It also clarifies the central role played by the earth's gravitational field in walking and running, and suggests that the human species exploits the constancy of that field to move anywhere on the planet with a minimum expenditure of energy. A prediction of the theory was that the legs were simply following pelvic motion. This suggestion was greeted with considerable skepticism by the gait-analysis community, which considered the trunk to be a passive unit carried by the legs.

The basic objection to the theory of the "spinal-engine" was the lack of understanding of the precise role of the legs. The solution eluded us until the early 1990s when Vleeming (1992) and Van Wingerden et al (1993) extended the anatomical dissections of Bogduk by exploring the layout of the ligaments across the sacro-iliac joint (SIJ). Their descriptions supplied the necessary information to explain how the legs could interact with the spine in locomotion.

Pelvic rotation and human gait

In its elementary form, human gait can be reduced to rotating the pelvis in the horizontal plane using a musculature that is more or less parallel to the spine (Figure 1).

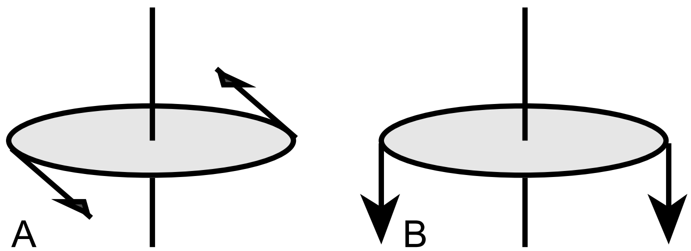


Figure 1: A Efficient axial rotation of the pelvis requires the application of forces in the horizontal plane. Such an arrangement is not physiological. **B Most** forces acting on the pelvis are substantially parallel to the axis of rotation. Determining how the pelvis can be axially rotated with such an arrangement is the purpose of the spinal-engine theory.

Two schools of thought have emerged over the years regarding this question. The first and oldest idea was that the legs played a primary role in human gait. Walking was simply a motion of the legs carrying its passive passenger, the trunk (Figure 2A). In contrast, the theory of the spinal-engine held that the spine was the predominant machinery involved with gait as inherited from our ancestor, the fish. Since both legs and spine are involved in locomotion, the problem is to elucidate their respective roles. This can be done by considering the logical implications of two basic hypotheses:

Hypothesis 1: The legs rotate the pelvis

The first hypothesis considers whether or not a leg can cause the pelvis to rotate. Suppose that the legs do rotate the pelvis. Conservation of the angular momentum requires that a counter rotation be applied by the leg to the ground (Figure 2B).

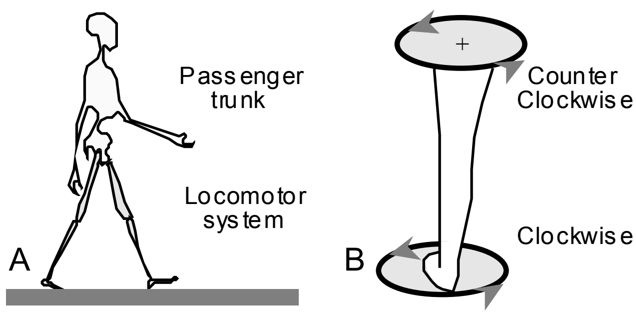


Figure 2: A Classical theory of gait, in which the trunk is passively carried by the legs. **B** A counter-clockwise torque applied to the pelvis must be balanced by an opposite clockwise torque to the ground. This is not observed. Hence, the leg cannot directly rotate the pelvis.

Force-plate data indicates that very little torque is applied to the ground during walking. Running on tiptoe excludes any significant torque transfer at the foot/ground interface. These observations suggest that the legs do not transmit torque to the ground; therefore, conservation of the angular momentum implies that no torque is transmitted to the pelvis either. Since the pelvis does rotate, the question is to determine what is responsible for pelvic rotation.

Hypothesis 2: The spine drives the pelvis to rotate

The spinal-engine theory attempts to explain how the spine contributes to human locomotion. In substance, the lordotic spine converts a lateral bending movement into an axial torque driving pelvic rotation (Figure 3A). This is the so-called coupled motion of the spine.

The theory predicts that legless individuals would "walk" on their ischium by keeping a normal spinal motion and normal EMG pattern for the trunk musculature. This has been verified on individuals, such as the young man shown in Figure 3B (Gracovetsky 1988).

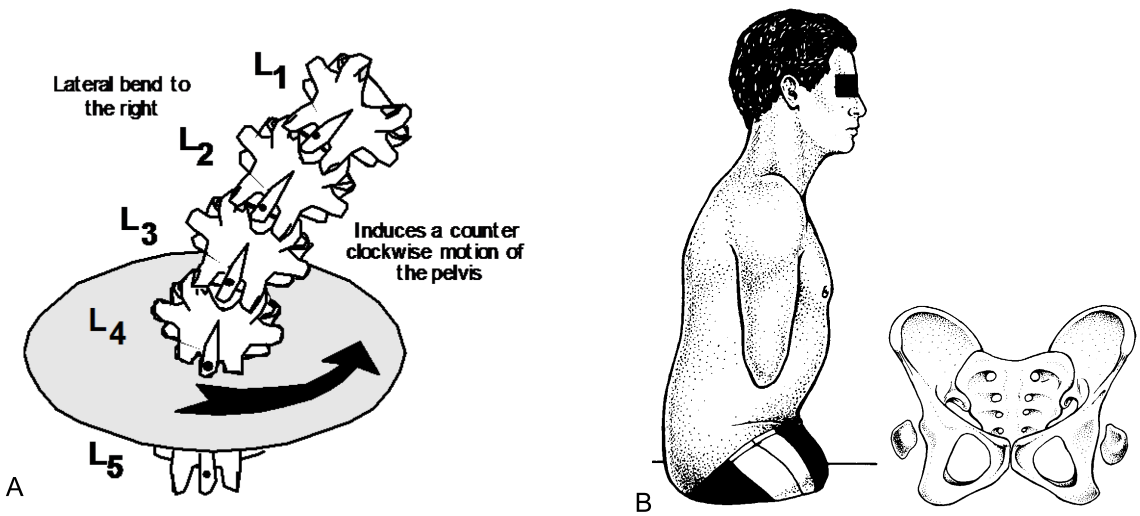


Figure 3 A The spinal engine theory hinges on the concept of the coupled motion of the spine, whereby a lateral bend of the spine induces an axial torque driving the pelvis. **B** Lateral view of a subject with no legs and reduced upper extremities. Radiographic AP view of the pelvis showing clearly the absence of lower extremities.

Kinematic and EMG studies demonstrated the striking similarities between his pattern of motion and that of a normal gait, except for the amplitude of the movements. The contribution of the spine was found to be consistent with the findings of Gregerson and Lucas in 1967 (Figure 4).

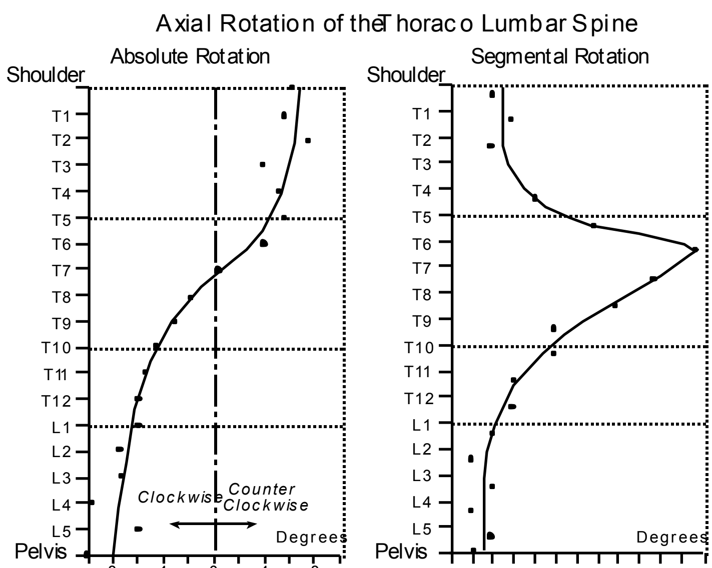


Figure 4: Gregerson and Lucas implanted pins in the spinous processes of the thoracolumbar spine and measured their motion (axial rotation) during gait. Note the important contribution of the thoracic spine to the counter rotation of pelvis and shoulder.

Absolute rotation: measured rotation with respect to T_7 .

Segmental rotation: rotation of each intervertebral joint with respect to its inferior neighbor.

Hence, there appear to be no contradictions between the proposed theory and the available data. This does not mean that the theory is correct. It simply means that it has not been proven wrong to date.

<u>Why the legs?</u>

Human bipedal locomotion can be achieved without legs. Indeed, we can “walk” on our knees without any fundamental modifications to our spinal motion, except perhaps for an enhanced amplitude of movement; this demonstrates that the part of the leg below the knee is secondary in locomotion, a feature exploited by the makers of prostheses. However, besides amplifying the motion of the pelvis, there is a more fundamental reason for the evolution of the lower extremities.

Increasing velocity requires increasing the power available for locomotion. To increase power means to increase muscular mass. The expansion of *erectores spinae* is restricted by the contents of the abdominal cavity; and therefore, the increase in muscle mass must be located outside the trunk, such as with the hip extensors (Gracovetsky 1990). The hip extensors' power is returned to the spinal-engine via the ligamentous structure described by Van Wingerden et al (1993) in their study of the SIJ.

One problem remains: The unsupported spine collapses under a mass of two kg or so. Yet, this apparent weakness allows fine movements requiring little energy expenditure to occur, a very desirable feature. However, in order to use the greater power produced by the hip extensors, the spine must first be strengthened, as will be seen later on.

Merging the contributions of the spine with that of the legs in locomotion

In order to explain the contributions of the spine and legs in human gait, we must keep in mind the need to axially rotate the pelvis. This is achieved by a complex sequence of events which can be summarized as follows:

1- In running or walking, the hip extensors fire as the toe pushes the ground. The muscle power is directly transmitted to the spine and trunk via two distinct but complementary pathways:

1.1 For *biceps femoris* (BF): The *sacro-tuberous* ligament extends the action of the *biceps femoris* all the way up the rib cage (Figure 5A). In addition, this ligament crosses over the *posterior superior iliac crest* and continues on as the *lumbar intermuscular aponeurosis* (LIA) Bogduk & Twomey (1987). The LIA has a direct link with the lumbar transverse processes via *iliocostalis lumborum* and *longissimus lumborum* (LL), (Figure 5B), as well as the spinous processes via *multifidus* (*Mult*).

1.2 For *gluteus maximus*: *Gluteus maximus* (GM) is connected to the *lumbodorsal fascia (LF)*, itself linked with *latissimus dorsi (LD)* and the upper extremities (Figure 5C).

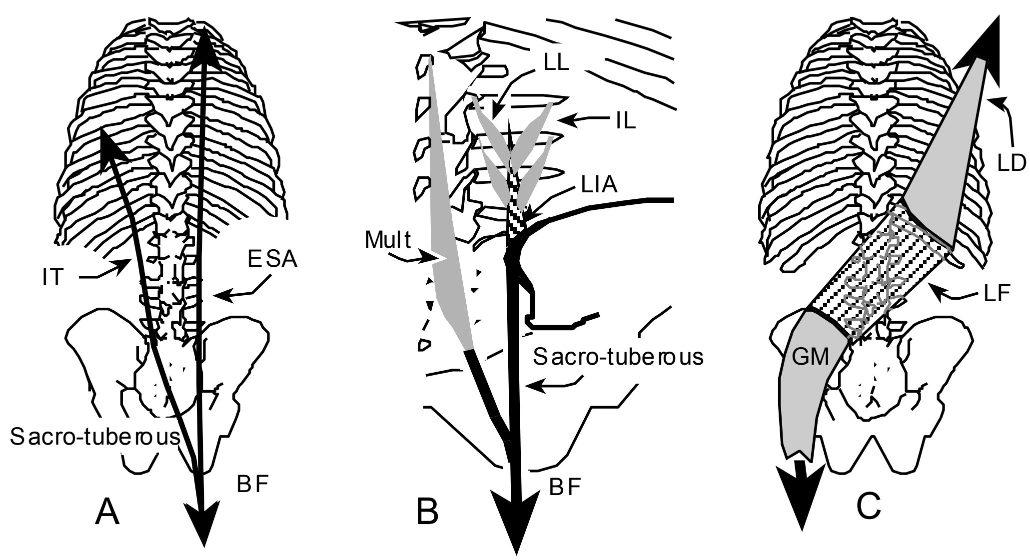


Figure 5: A The *biceps femoris* is directly connected to the upper trunk via the *sacro-tuberous* ligament, the *erectores spinae* apeunorosis (ESA) and *iliocostalis thoracis* (IT). **B** Enlarged view of the lumbar spine area showing the link between *biceps femoris* (BF), the *lumbar intermuscular aponeurosis* (LIA), *longissimus lumborum* (LL), *iliocostalis lumborum* (IL) and *multifidus* (*Mult*). **C** Relations among *gluteus maximus* (GM), *lumbodorsal fascia* (LF) and *latissimus dorsi* (LD).

As a consequence, firing the hip extensors extends and raises the trunk in the sagittal plane. The chemical energy liberated within the muscles is now converted, by the rising trunk, into potential energy stored in the gravitational field. When a person is running, so much energy needs to be stored that the necessary rise in the center of gravity forces the runner to become airborne.

2- During flight (running) or single-stance phase (walking), the force of compression applied to the spine is minimum (Figure 6).

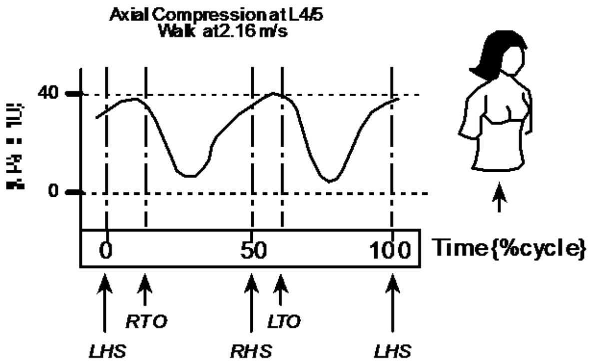


Figure 6. Axial compression on the L4/5 joint. The compression is maximal after heel strike (pulse delayed as it travels upwards) and minimum during the double-stance phase. *LHS:* left heel strike. *RTO:* right toe off.

The spine can assume the proper lateral bending shape in preparation for landing (heel strike). To increase the stride, the *acetabulum* is brought forward by the rotating pelvis. Little force is required to alter the spinal shape, and hence this process is not taxing the *erectores spinae*. The trunk now falls back towards the ground, and in so doing converts its potential energy into kinetic form.

3- At heel strike, a compressive pulse is generated at the foot/ground interface. This compressive pulse can be quite large. When running at 3.8 m/s, pulses can reach 9.55 g (Clarke et al 1985). This compressive pulse recuperates the trunk's kinetic energy.

4- The pulse travels up the leg and pelvic SIJ into the spine. To ensure synchronization with the spinal motion, the pulse is reshaped and delayed by the viscoelastic structure of collagen at the knee, the hip joints, the *sacro-tuberous* ligament and the *lumbodorsal fascia*. This filtering process is essential to provide a perfectly matched pulse to the spine kinematics regardless of ground-surface hardness so that a maximum transfer of energy occurs. The consequences of a mismatch can be appreciated when running on soft sand: the kinetic energy of the falling trunk is dissipated into the shifting sand; the weakened pulse cannot be properly reshaped by the knee and the resulting mismatch with the spine further increases the energy loss. To compensate for that loss, the runner fires his (inefficient) abdominals to maintain the necessary pelvic rotation, rapidly resulting in exhaustion. The relation between the elasticity of a running surface and shoes is of particular concern for high performance athletes who know that some surfaces are “faster” than others.

5- The energy carried by the compressive pulse is sequentially delivered to each intervertebral joint in ascending order so that no energy is left at the upper cervical and head interface. It is widely believed that the disk acts as a “shock absorber” attenuating the heel strike impact before it reaches the head. This popular view is partially true except that the pulse energy is not absorbed (lost) into heat but is converted (used) by the coupled motion of the spine to rotate the IV joint.

Indeed, the timing is critical. The intervertebral joint must first be bent laterally and fully rotated axially to advance the *acetabulum* into the direction of locomotion. Only then, as the spine begins to unwind, can the pulse reach the spine. Like a child on a swing reversing its motion just before receiving a push, the unwinding spinal motion is accelerated by the kick of energy it receives from the compressive pulse. Improper timing may be hazardous as the out-of-sync pulse may increase the torque supported by the intervertebral joint beyond physiological limits. Such an event may occur when the ground surface is either higher or lower than expected.

Gait experiments by Cappozzo in 1983 (Figure 7) suggest that the torque through L4 can exceed the 20 Nm quasi static limit of lumbar intervertebral joints (Farfan 1973).

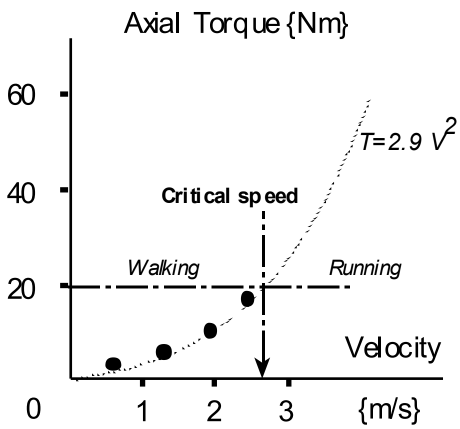


Figure 7 The measured torque across L4/5 during walking has been extrapolated for higher velocities.

By compressing the IV joint, the heel strike pulse stiffens the spine and increases its torque strength beyond the critical 20 Nm limit. The high level of torque is necessary to arrest and reverse the lateral bending of the trunk, while spinal lordosis induces the high axial torque needed to drive the pelvis.

This sequence of events is repeated for each IV joint as the compressive pulse propagates upwards, and the energy delivered to the IV joints of the thoraco-lumbar spine is used to counter rotate shoulders and pelvis. This provides the basic movement of locomotion, which is amplified by the legs. Hence, the hip extensors can be seen as axial rotators of the spine, pelvis and shoulders.

6- The weakened compressive pulse exits the thoracic spine and travels into the cervical spine. Using the same principles as before, the pulse generates an axial torque. However, the peculiar shape and arrangement of the cervical facets reverses the direction of this induced axial torque. The net effect is to oppose and de facto cancel the motion of the shoulders so that the head remains steady. It is speculated that this arrangement evolved out of the necessity of stabilizing the motion of the head (semi-circular canal and eyes sensors) during gait.

The legs have the required muscle mass to release enough chemical energy for running or walking. The legs also provide contact with the ground and modulate the timing, duration and amplitude of the energy pulses generated at heel strike before transmitting them to the spine. The spine capitalizes on this energy to fuel its axial rotation, which in turn rotates the pelvis. Thus the legs perform these functions to assure gait modulation and velocity for a wide range of ground conditions.

Details of spinal motion during the gait cycle

The leg and pelvic motion have been analyzed at length in the literature. The specific movements of the spine are less well known and have been measured by a high-resolution opto-electronic system tracking the motion of 14 markers placed strategically over the spinous processes and other reference points (Figure 8).

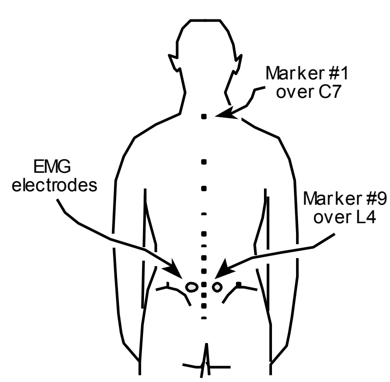
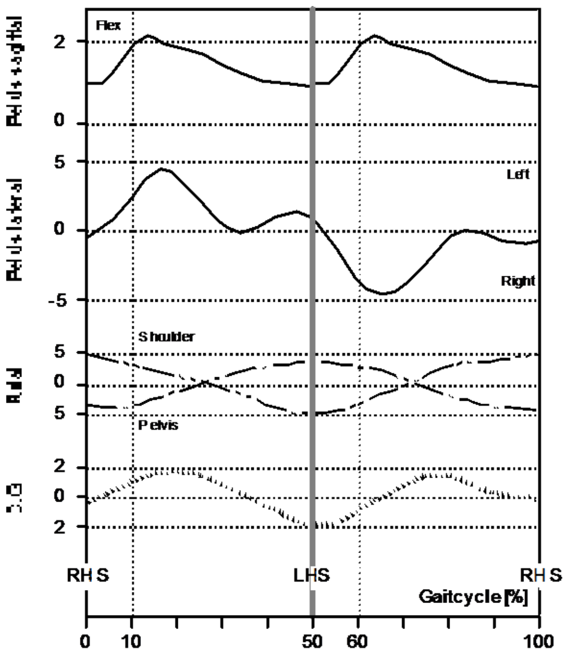


Figure 8 Position of 14 skin markers, 12 above the spine and two above the iliac crest and two EMG surface electrodes (bilateral at the L_5 level over *multifidus*).

From it, the kinematics of lumbar intervertebral joints can be estimated (Gracovetsky 1995), as well as the variations in lordosis during gait (Figure 9). Also, the torque induced at the L4/5 level can be calculated; the relative contributions of the *annulus* fibrosus *and* facets to the total torque transmission are shown in Figure 10.



Definitions: *pelvis sagittal and lateral:* rotation of pelvis in the sagittal and frontal planes. *Axial:* rotation of pelvis and shoulder in the horizontal plane. *C.G.:* vertical displacement of the center of gravity. RMS: right heel strike

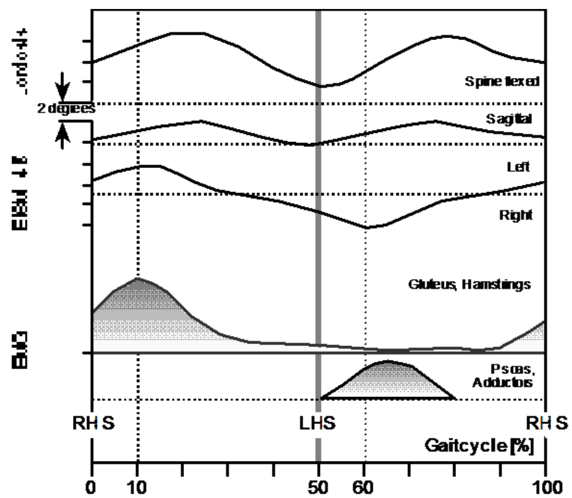


Figure 9 Relative motion of the L4/5 intervertebral joint and changes in lordosis during gait cycle.

Lordosis: variation of the estimate of the lumbosacral angle. *EISM*$_{4/5}$: estimated rotation of the $L_{4/5}$ in the sagittal and frontal planes. *EMG:* integrated EMG of muscles.

Indeed, the torque is transmitted by the intervertebral joints via a dual (facets and *annulus*), but complementary, mechanism. The central feature of this arrangement is to spread the generation and transmission of torque over the entire gait cycle. Specifically, when the pelvic rotation is at its maximum, the interlocking facets transmit virtually all the available torque, while during the double-stance phase, the facets are substantially aligned and cannot transmit any torque.

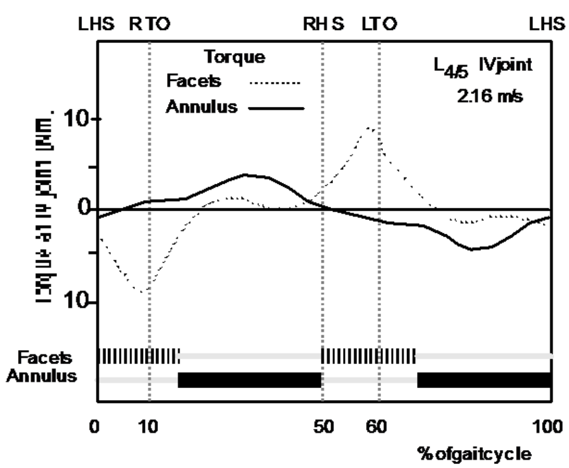


Figure 10 Contribution of *annulus* and facets to the total torque transmitted through L4/5 during gait cycle (walk at 2.16 m/s). The duty cycles of facets and annulus illustrate the complementary nature of these structures in the generation and transmission of torque.

In contrast, the *annulus fibrosus*, made of viscoelastic collagen fibers, responds particularly well to changes in angular rotation velocity. Hence, the torque transmitted by the *annulus* is maximum when the velocity is maximum (double-stance), which corresponds precisely to the instant when the facets' transmission is minimum. Conversely, at heel strike when the facets are most effective, the reversal in pelvic motion brings the angular velocity to zero and the *annulus* becomes inefficient.

Therefore, during gait, the torque needed to drive the pelvis is pulsating through both facets and disc, rhythmically and repeatedly as illustrated by their duty cycles in Figure 10. This prevents the continuous loading of a single structure with the attendant high probability of failure.

This model of a dynamic role for the spine involving torsion and compression during locomotion has important ramifications for the diagnosis and treatment of spinal disorders:

- The spine must be impulse loaded. Wearing soles that are too soft is not recommended because they absorb and dissipate the impulse intended for the spine to use for locomotion. The viscoelastic nature of biological material prevents it from sustaining constant loads for extended periods of time. A constant blood pressure would deform and damage the arteries, and prevent the heart from resting. Similarly, the regular sagittal oscillating motion of the spine of the hiker carrying a backpack coupled with the anterior posterior motion of the pelvis prevents the lumbodorsal fascia from continuously transmitting forces. During the double stance, the lordotic spine switches on the erectores spinae muscles and slackens the posterior ligamentous system. Conversely, at heel strike, the posterior ligamentous system being tightened can transmit forces, thereby permitting the erectores to relax and rest. Hence, muscles and ligaments alternatively time share the forces transmitted across the SIJ, delaying the onset of fatigue of the back.

- Surgery such as fusion or the implantation of metallic plates and screws intended to stabilize the spinal "column" is not recommended, unless there are no good alternatives. The development of soft stabilization techniques without fusion appears to be a promising strategy for strengthening the spine.

- Diagnosis of spinal disorders ought to be dynamic and not static. In particular, static radiographs are of little use for functional assessment. Normality can be expected to be dependent upon the activity undertaken rather than an absolute decision across the board.

CONCLUSION

1. We propose that gait is the result of a sequential transformation of energy.
2. Beginning with the legs, muscular chemical energy is first used to lift the body into the earth's gravitational field where the chemical energy is stored in potential form.
3. When the body falls downwards, this potential energy is converted into kinetic energy which is in turn stored into a compressive pulse at heel strike.
4. The pulse properly filtered by the knees and the massive ligamentous structure across the SIJ travels upwards.
5. The energy is then distributed to each spinal joint to counter-rotate pelvis and shoulder, while the head is stabilized by derotating the shoulders.

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