

SCIENTIFIC PHYSICAL THERAPY

Function of the Human Rib Cage

The role of respiration, rib mechanics and neural reflexes in coordinated movement and stability of the rib cage

Sam Betts, PT, MOMT

Respiratory Function of the Ribs

In addition to protecting the intrathoracic organs, the ribs provide two essential respiratory functions. First, they constitute the structural elements that carry the compressive stresses that balance the pressure difference across the chest wall. Second, the ribs transform intercostal muscle shortening into lung volume expansion.¹

Consider the fundamental differences between the cardiac pump and the respiratory pump. For the heart, the pressure inside the chamber is higher than the surrounding pressure and the wall must carry tension to balance this pressure difference. During contraction, work in the wall is done by reducing the volume of the chamber. This requirement is fulfilled by the properties of muscle; namely, it carries tension and performs work as it shortens. In contrast, for the respiratory pump, the pressure inside the wall is lower than the surrounding pressure and work is done by increasing the volume enclosed by the wall. The properties of muscle do not match these requirements. One solution to this problem is to reverse the curvature of the wall. This is the case for the diaphragm. As it is concave outward, it carries the tension to balance the pressure difference across the wall and induce an increase in the enclosed volume

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when it shortens. However, the rib cage is concave inward, so it requires elements that carry compression and that convert muscle shortening into volume expansion. This is the case for the ribs. Muscle contraction causes cranial elevation of the rib cage and hence muscle forces are expansive rather than compressive in nature to intrathoracic volume.

The rib cage is a mechanism in which the bony elements either move freely about their joints or are stabilized in a particular position against pneumatic or postural loads by the controlled and coordinated system of forces exerted by the respiratory muscles.²

Functional anatomy of the rib cage muscles

The entire respiratory system of respiratory muscles are assumed to act under central control to change length in a coordinated way so that the rib cage adopts a particular shape and to produce a coordinated system of forces so that the rib cage is in equilibrium under imposed pneumatic and postural loads.²

The scalene muscles

Recent EMG studies on the scalene muscles have indicated that they are consistently active in humans during quiet respiration.³ Electrical activity in both the scalenes and the parasternal intercostals usually start together with the beginning of inspiration, increase progressively as inspiration proceeds, reaches its peak at the end of the inspiratory phase and lasts into the early part of the subsequent expiration.³ When subjects attempt to inspire with the rib cage alone to displace the diaphragm paradoxically inward, the inspiratory EMG activity in both the scalenes and the parasternal intercostals markedly increases.

In subjects performing diaphragmatic isovolume maneuvers (Valsalva's) each subject contracting the diaphragm at FRC against a closed glottis caused a complete suppression of EMG activity of both the scalenes and the parasternal intercostals.

When subjects attempted to inspire with the diaphragm alone, causing a greater increase in abdominal A-P di-

ameter and a smaller increase in rib cage A-P diameter than during natural breathing, the scalene inspiratory EMG activity markedly decreased, whereas the parasternal inspiratory EMG activity increased. This was accompanied by a large decrease in upper rib cage AP diameter.³ This suggests that as the scalenes may be selectively inhibited by diaphragmatic breathing, the neural pathway governing scalene activation differs from those driving the diaphragm and parasternal intercostals.

Scalenes are active with the parasternal intercostals during quiet breathing suggesting that these muscles need to be activated with the diaphragm in a coordinated manner for quiet breathing to occur and for the rib cage to move with a single degree of freedom.³

The intercostal muscles

Recent work has shown that the parasternal intercostals (sternal portion of the internal intercostal muscle) are active during inspiration, with a pattern of activity that resembles the diaphragm and that they



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act in concert with the scalenes to expand the upper rib cage or to prevent it from being drawn inward by the action of the diaphragm.⁴ Selective denervation of the parasternal intercostals in one interspace eliminates its shortening during respiration. This is evidence that the contraction of the parasternal is agonistic for inspiration and the cause of rib displacement, rather than the consequence of rib motion.⁵ In addition, this observation suggests that the external intercostals and the levator costae do not play a major role in causing inspiratory elevation of the ribs. If

they did, then the selectively denervated parasternal intercostals would continue to shorten a certain amount passively during respiration.⁵

Graded increase in inspiratory airflow resistance causes a progressive inhibition of parasternal intercostal activity and a gradual facilitation of external intercostal and levator costae muscle activity. Sectioning of the phrenic nerve did not alter the response of the parasternal intercostal muscle activity but markedly reduced or abolished activity of the external intercostal and levator costae muscles. The authors con-

clude that reflex facilitatory activity of these muscles during inspiratory resistive loading results primarily from the collapsing action of the diaphragm on the cranial portion of the rib cage and the consequent lengthening of these muscles. When needed during inspiratory loading, the external intercostals and levator costae muscles are capable of significant expansion of the rib cage and lung.^{5, 6}

A more recent study further investigated the activation during respiration of the external intercostals and the interosseous part of the internal intercostals.⁷ The authors

found that the external intercostals in many areas of the rib cage shorten during passive inflation whereas the interosseous internal intercostals lengthen. Therefore, the external intercostals have an inspiratory mechanical advantage and the internal intercostals (interosseous part) have an expiratory mechanical advantage. However, the magnitudes of the mechanical advantages vary throughout the rib cage, such that the inspiratory advantage of the external intercostals is greatest in the more rostral interspaces and the expiratory advantage of the internal intercostals is greatest in the ventral portion of the caudal interspaces. The mass of the external intercostal muscle is greater in the dorsal half of the ribcage and the mass of the internal intercostal muscle is greatest in the ventral half. As a result, the external intercostals in the dorsal aspect of the rostral segments (upper six interspaces) have a significant inspiratory effect on the ribcage and the internal intercostals in the ventral aspect of the caudal segments have a large expiratory effect in all segments of the ribcage.

The study used analysis of muscle lengths during maximal passive inflation, to test the theorized mechanical advantage of each muscle rather than electrical evidence of muscle activity.

The sternocleidomastoid

During contraction, upper rib cage expansion and cranial motion of the sternum is expected. In patients with high tetraplegia the 11th cranial nerve innervating the SCM is preserved, whilst other neck and inspiratory muscles are paralyzed. The SCM muscles profoundly hypertrophy in these patients, but can only sustain ventilation for a few hours. The SCM is not active during quiet breathing, unlike the scalenes.⁵

The triangularis sterni (*sternocostalis/ transversus thoracis*)

Fibers originate from the dorsal aspect of the distal half of the sternum and run cranially and laterally to insert into the inner surface of the costal cartilages of ribs 2-7.

When the triangularis sterni acts alone in apnoeic animals,

it causes a caudal displacement of the ribs and a cranial displacement of the sternum, resulting in a rise in pleural pressure and a decrease in lung volume. It therefore has an expiratory action to the rib cage.

In dogs, this muscle is active in quiet expiration. It serves to support inspiration by initiating inspiration from a lower volume than relaxation volume and the relaxation of triangularis sterni at the beginning of inspiration results in rib cage expansion, which is passive in nature.⁵ In humans it is not active during quiet inspiration, however during expiration below functional residual capacity during speech, laughing and coughing, the triangularis sterni is recruited.

The diaphragm

The diaphragm, acting through a fall in pleural pressure, produces a collapse of the cranial portion of the rib cage when it contracts. It expands the caudal portion of the ribcage by two mechanisms. First, the fibers of the costal diaphragm insert on the upper margins of the lower

ribs and are oriented cranially, such that they are apposed directly to the inner aspect of the caudal ribcage. Hence, when these fibers contract, the force they exert has the effect of lifting the lower ribs and rotating them outward. Second, the contracting diaphragm causes a rise in abdominal pressure and this rise of pressure is transmitted through the apposed portion of the muscle so as to push the caudal ribcage outward.⁶

The abdominal muscles

Muscles of the anterolateral abdominal wall have been traditionally considered muscles of expiration and because of their insertions, they are usually thought to pull the lower ribs down and deflate the ribs. However, contraction of these muscles also increases intra-abdominal pressure, which by causing passive distension of the diaphragm and acting over its zone of opposition to the lower rib cage, tends to expand the lower rib cage.⁸ This inflationary component of the abdominal muscles action may in fact counter-balance or even dominate their insertional deflatory force and in

the dog actually expands during isolated contraction of the external oblique.⁸

Rectus abdominis contraction increases the rib cage diameter, pulls the rib cage caudally, and decreases the ribcage AP diameter. It thus makes the rib cage more elliptical. On the other hand, the external oblique acts primarily to contract the lower ribcage along its transverse dimension, making it cylindrical. These two muscles' work may distort the ribcage in either direction, depending on the relative strengths of contraction of each muscle.⁸ According to these authors, the balance between the force of the muscle attachments deflating the ribcage and the rise in abdominal pressure acting on the diaphragm and inflating the lower ribcage determines the action of the abdominal muscles in the rib cage.

Interactions of the rib cage muscles

External intercostal- external intercostal interaction

No evidence has been found for the interaction of external

intercostal muscles in different interspaces. Initial denervation of the external intercostal muscle in a given interspace resulted in an increase in external shortening in the adjacent interspace, without an increase in the level of muscle activity.⁹ This suggests that the external intercostal muscles are arranged in series. Consequently, rib displacements caused by these muscles are additive and therefore maximized.

Parasternal- parasternal interaction

During quiet breathing, parasternal shortening in a given interspace is virtually abolished after its denervation, suggesting that the mechanical interaction of parasternal intercostals among different parasternals is limited. However, after phrenicotomy the parasternal whilst still denervated still shortens a significant amount, suggesting a greater interaction among interspaces than during quiet breathing.

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External intercostal-parasternal interaction

Recent observations in dogs have shown that after denervation in a given interspace, the external intercostal shortening although less, is still persistent during resting breathing, but is markedly reduced following parasternal denervation in the same interspace.⁹ These findings indicate that the two muscles in the interspace are arranged in parallel and that during quiet breathing parasternal contraction contributes to external intercostal shortening. The interaction of these two groups of muscles achieves the desired expansion of the rib cage under different circumstances.⁵

Alterations of the ribcage muscle action with hyperinflation

Hyperinflation is a common abnormality accompanying disease accompanying airflow obstruction, e.g. severe asthma, COPD. Hyperinflation disadvantages the diaphragm and in severe cases may have a deflationary ef-

fect on the ribcage. In patients with chronic airflow limitation who are severely hyperinflated, a paradoxical motion of the ribcage is observed during tidal breathing (Hoover's sign).

During hyperinflation, the inspiratory intercostal muscles may be much better preserved than the diaphragm, not having to shorten/ contract as hard as the diaphragm. In normal subjects, hyperinflation changes breathing pattern, such that the inspiratory rib cage displacement is associated with abdominal in drawing.⁵

Phrenic-to-intercostal reflexes

Paralysis of the phrenic nerve in dogs causes a non-vagal, non-chemical increase in the activity of the inspiratory intercostal muscles (parasternal intercostals, external intercostals and levator costae) Stimulation of the ipsilateral and contralateral C5 phrenic nerve roots caused an immediate reduction in the inspiratory intercostal activity. Diaphragmatic receptors may reflexively inhibit effer-

ent activity to the inspiratory intercostal muscles, in particular the external intercostals and the levator costae.¹⁰ These observations are fully consistent with the recent conclusion that the increased inspiratory intercostal activity observed after phrenic nerve blockade may result from the release of an inhibitory reflex originating from the contracting diaphragm.¹¹

The simplest hypothesis would be that the intercostal inhibition seen by stimulation of the phrenic nerve and the intercostal facilitation caused by phrenic nerve blockade in each of these studies are related to the same reflex mechanism.

In addition, the phrenic-to-intercostal inhibitory reflex would already operate during quiet breathing and this would imply that the reflex arises in low threshold mechanoreceptors.¹⁰

A similar mechanism was also mentioned previously whereby increases to airflow resistance increased external intercostal and levator costae activity, but no parasternal intercostal activity⁶; this served to confirm that the activation of parasternal

intercostals is primarily governed by supraspinal mechanisms. The fact that phrenic afferent stimulation caused substantially weaker inhibition of the parasternal intercostals than in the external intercostals and levator costae, indicates that the latter muscles are under more flexible control than the former. However, by demonstrating that the parasternal intercostal activity was inhibited by stimulation of the phrenic nerve the phrenic-to-intercostal reflex has a supraspinal component.¹⁰

A Study by De Troyer et al¹² found that application of force to the central tendon of the diaphragm caused a graded reflex reduction in inspiratory intercostal activity and was associated with a decrease in inspiratory duration and was attenuated after the sectioning of phrenic nerve roots. In

contrast, no change in inspiratory intercostal activity was found during high frequency mechanical vibration was applied to the central tendon, to stimulate the diaphragmatic muscle spindles. The authors conclude that tension recep-

hibitory inputs from diaphragmatic tension-sensitive receptors causes the observed increased intercostal activity in studies.

Costovertebral joint reflexes

Strong evidence suggests that the external intercostal and levator costae alpha-motoneurons, but not the parasternal alpha-motoneurons, receive abundant projections from the mechanoreceptors of the costovertebral joints.¹³ These differences in segmental and intersegmental connec-



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tors in the diaphragm, not muscle spindles, induce reflex inhibition of intercostal activity. The expression of this reflex probably involves supraspinal structures in the brain stem. This provides evidence that the removal of in-

tions are such that when the normal inspiratory cranial motion of the ribs in dogs is reduced or reversed into an inspiratory caudal motion, the external intercostal and levator costae muscles show increased EMG activity but



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parasternal activity remains unaltered. This again supports the theory that parasternal intercostal activity is governed primarily by supraspinal mechanisms.

A study by Shannon¹⁴ demonstrated that costovertebral joint movement in either the inspiratory or expiratory direction had an inhibitory effect on inspiratory activity and prolonged the expiration time and that the effects seen were due to stimulation of mechanoreceptors in the joint capsules of costovertebral joints. He concluded that the mechanoreceptor stimulation terminates inspiratory activity and during expiration, they would tend to inhibit the onset of inspiration, thus prolonging expiration. He indicates that afferent information from the joint mechanoreceptors is exerting its effect primarily on the medullary pontine rhythm generator.¹⁴ He did not rule out the possibility that costovertebral joint mechanoreceptors also affect phrenic activity via segmental pathways and that the decreased rate of phrenic activity observed during sustained rib displacement could result in part from tonic inhibition via segmental path-

ways. He also noted two types of responses to costovertebral joint motion via chest compression and isolated costovertebral joint movements. The type I response was a shortened inspiratory and increased expiratory time and the type II response was a shortened inspiratory and expiratory time.

There were limited studies to be found relating costovertebral joint motion to respiratory changes and the mechanisms for such respiratory changes still seem unclear from the current literature.

The role of the rib cage and respiration in stabilization of the spine.

Motion of the ribs

During inspiration, there is a change in the lateral and antero-posterior thorax dimensions. The torso has changed shape, so it has deformed. This is attributed to movements of the rib cage, but can the rib cage be reasonably said to have deformed? Its shape has changed, but from surface measurements, one cannot tell whether this is due to the ribs and sternum moving as rigid bodies, re-

sulting in an overall change in shape, or whether the ribs themselves have bent. The assumption during analysis of biomechanical movements of the rib cage is that the ribs and sternum are rigid bodies, without a change in their overall shape, moving around more mobile posterior costotransverse and costovertebral joints. The assumption is that bending, twisting, elongation or compression of these structures plays a negligible role. This assumption of rigid body motion is based upon two arguments. First, the forces required to bend a human rib or costal cartilage is very much greater than those required to move a rib around its joints and if rib deformation occurred, very high muscular forces would have to occur during normal respiration. Second, the rib cage has evolved with at least 48 joints and it seems unlikely that such an elaborate system would have evolved if it "jammed" during normal movements and large forces were needed to deform components in order to move.¹⁵ The following biomechanical analysis of rib mechanics by Saumarez¹⁵ describes theo-

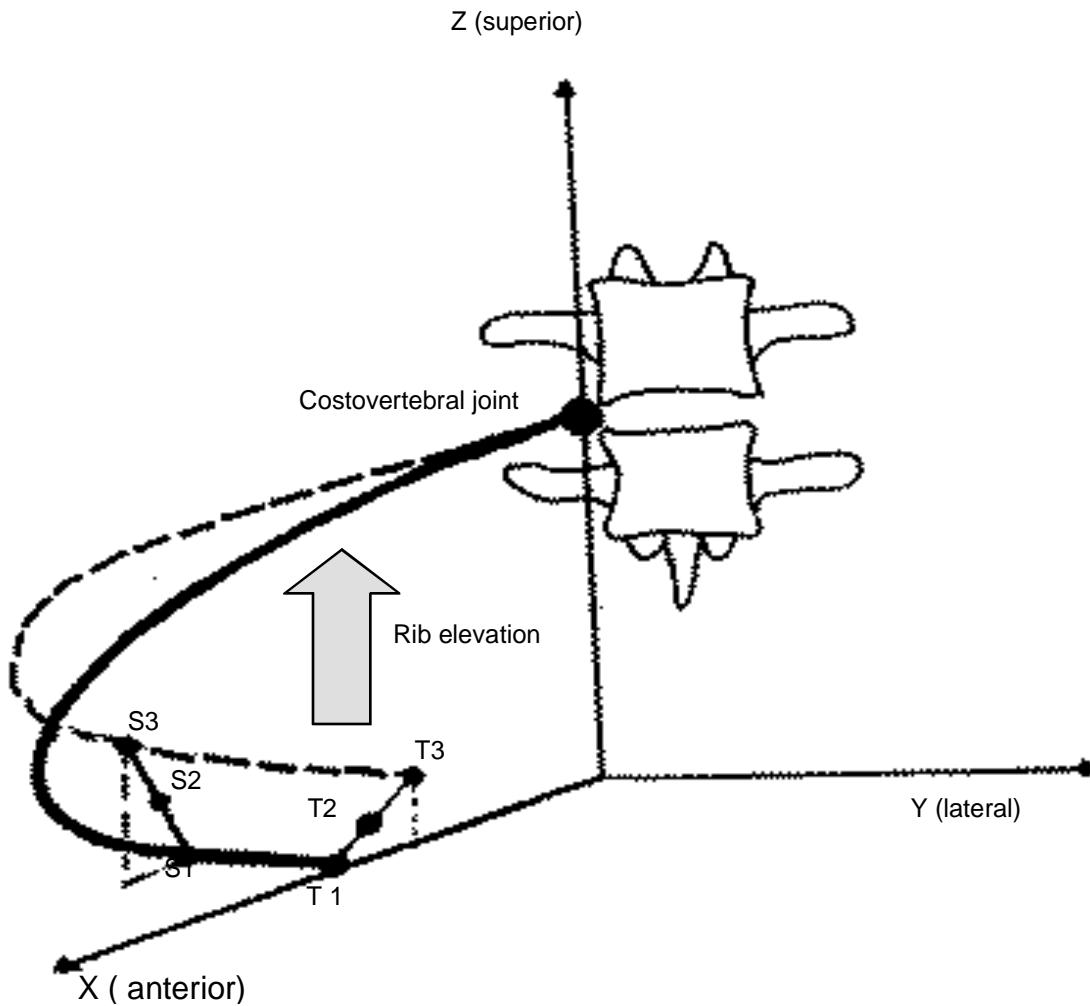


Fig. 1. As the rib rises, a point on the tip of the costal cartilage moves from T1 to T2 and then to T3 in a trajectory that is parallel to the saggital plane. At the same time, a point on the lateral border of the rib moves from point S1 to point S2 and then finally to point S3.

retical axes for rib motion based on computer generated modeling of the thoracic spine from cadaveric specimens. The author disputes the idea that rib motion could occur around a single fixed axis. Consider Figure 1. If the tip of the rib cartilage anteriorly, rises as shown, it starts from point t1 rising to fit the chondrosternal joint at point t2 and then rises to t3. These points, t_{1,2} and t₃ lie in the sagittal plane and if they have rotated about a single axis, that axis must be perpendicular (at 90°) to that plane. Using a coordinate system as shown in Fig 1, it is parallel to the y-axis.¹⁵ If we then take a point on the lateral aspect of the rib, s1, as the rib expands laterally, s1 will move to s2 and then to point s3. These points define motion in a plane that is inclined to the sagittal plane and so the axis describing their rotation, which is perpendicular to this plane cannot be parallel to the y-axis. If the rib is assumed to be rigid then it is concluded that the tip of the rib rotates about an axis parallel to the y-axis and the lateral border of the rib has rotated about an axis that is not parallel to the y-axis.

Therefore, the author concludes that the concept of a single fixed axis for the motion of a rib must be rejected. Axes will therefore not be identical and reflects the fact that describing the axis of rotation of a moving rigid body does not always describe the path the object took in moving from its initial to final positions. The author points out that there will be an infinite number of axes for a given sternal elevation. Once the direction of the axis is fixed by selecting a point on a line of constant sternal elevation, the position of the rib is fixed. Previous authors have failed

to appreciate that motions of the rib must be expressed as successive rotations about a shifting axis as the rib elevates.

Costovertebral and Costotransverse joint motion

An analysis for motion of ribs 2-6 is provided in the current model by Saumarez.¹⁵ for ribs 2-6. Lower ribs were left for further analysis due to the complexity of motion caused by the diaphragm.

Saumarez describes the costotransverse facet as approximately cylindrical with its axis pointing superiorly, anteriorly and medially. The demi-fac-

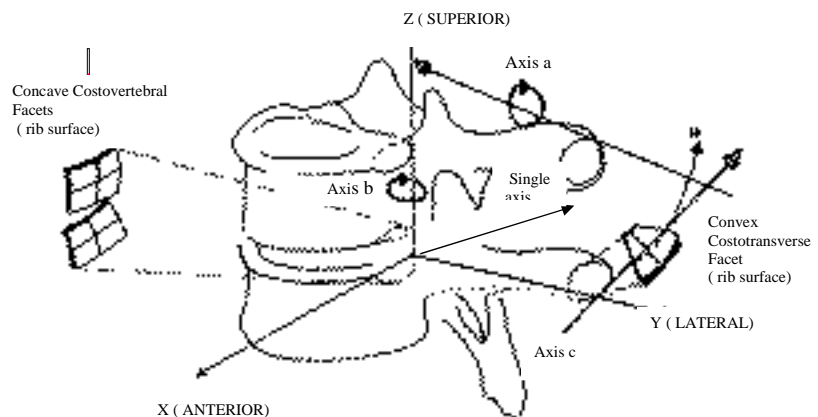
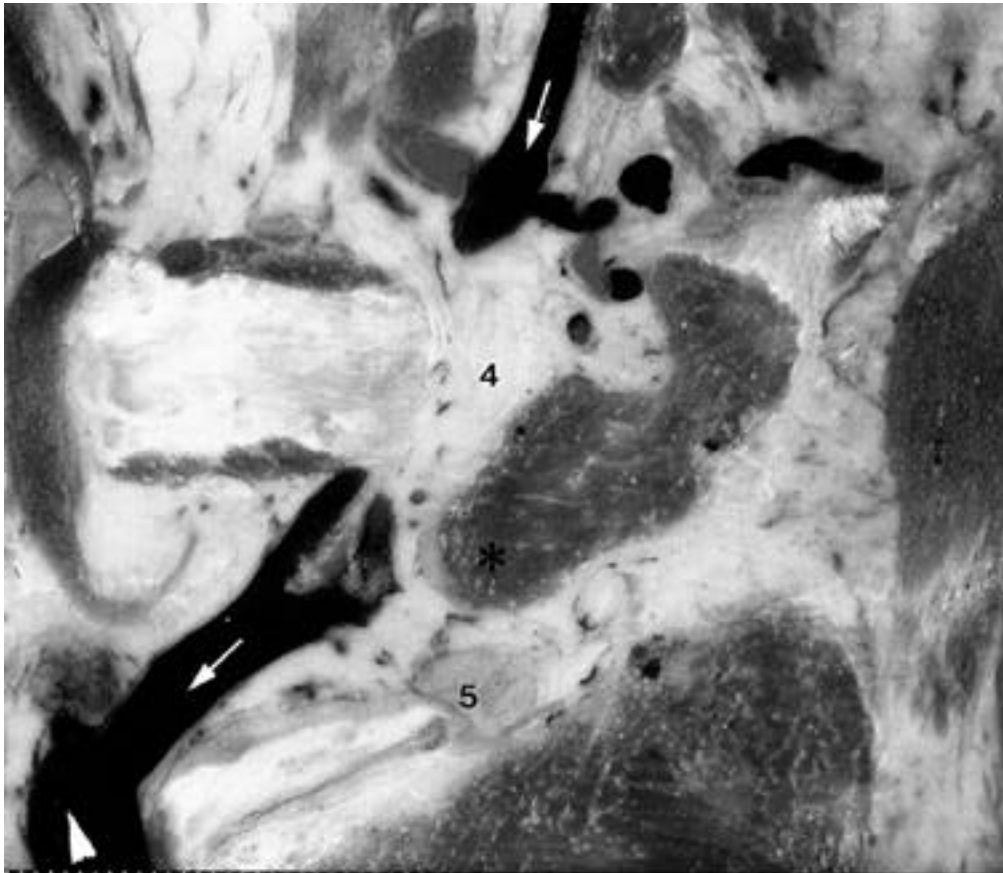


Figure 2: Diagram showing axes for rib motions. Approximate geometry of rib surfaces articulating with costovertebral and costotransverse joints are indicated. Arrows on axes "a" and "b" show the direction of rotation when tip of the rib rises and lateral border expands.

(Continued on Page 13)

Rauschning pathology series-Lumbar Spine



Severely degenerated lower lumbar spine of a 70-year-old man who a history of long-standing low back pain. This sagittal section through the lateral borders of the L4-L5 and L5-S1 discs illustrates the topographic relationships of the L4 and L5 nerves to the discs and the venous structures. The left iliac vein runs immediately anterior to the (degenerated) L5-S1 disc space and also receives the ascending lumbar vein at this level. The L5 nerve, snugly following the lower L5 endplate, is severely deformed by the posteriorly projecting spondylosis flanges. Inferiorly the L5 nerve is bounded by the ala of the sacrum, superiorly by the heavy transverse process of L5. The metric scale at the baseline illustrates that a few millimeters' scoliotic tilt could compress the L5 nerve outside its neuroforamen (far-out-syndrome).

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ets on each rib are locally concave. Their surfaces are oriented so that their superior and inferior borders lie on a concave surface so that the normal vectors to the midpoint of each facet converge (but don't intersect) laterally to the position of the costovertebral joint facets (see Fig. 2 below) The costotransverse surface has been represented as an approximate cylinder with a very slight curvature in the direction of its axis as shown. The costovertebral surfaces have been represented as bi-spheroidal, with the two radii of curvature centered on the normal vector to the midpoint of the facet. In order for these joints to move in order to reduce the possible amount of "misfit" there has to be some translation occurring with rotation of these joints. The author believes that it is this amount of gliding/translation that allows for small amounts of "misfit" at the joint surfaces to be tolerated. This criterion of "best fit" is describing rib translation that occurs during rotation of the rib, probably due to articular cartilage compression occurring with various loads. The author notes that

ribs commonly follow this normal path of "misfit" within predictable norms; however, most "misfit" occurs at the rib position of functional residual capacity. It is not known how closely ribs are constrained to move along trajectories of minimum misfit by the action of the intercostal muscles.

Axes of motion for costovertebral and costotransverse joints.

The costotransverse joint is approximately cylindrical and so the rib could be imagined to rotate about the axis of this cylinder that is shown in Figure 2 as axis "a." A rotation about this axis makes the tip of the rib move upward and laterally.¹⁵ The author defines a second axis "b" that must exist so that when the tip of the rib rotates about axis "a" the tip of the rib stays fitting the sternum This angle is perpendicular to the plane of the costovertebral joint facets and is parallel to the plane of the to the normal plane of the costotransverse joint (see Fig. 2) This is important because a rotation about axis "b" will not only cause the rib to fit the sternum, but will cause the costotransverse joints to

glide over each other. Therefore, rotations about this axis will cause very little misfit at the costotransverse joint, while allowing the rib to remain in contact with the sternum anteriorly. At the costovertebral facets, a rotation about axis "a" causes these joints to translate anteriorly. However, a concomitant rotation about axis "b" causes the facets to translate in the opposite direction, resulting in very little movement at the costovertebral joint facets. Another axis "c" is postulated by Saumarez, perpendicular to axes "a" and "b," allowing for deviations from this normal rib path. A rotation about axis "c" causes inferior motion of the tip of the rib and superior motion of its lateral border, causing considerable "misfit" at the costotransverse and costovertebral joints.¹⁵

My interpretation was that this represented a paradoxical breathing pattern with abdominal in-drawing and rib cage cranial elevation.

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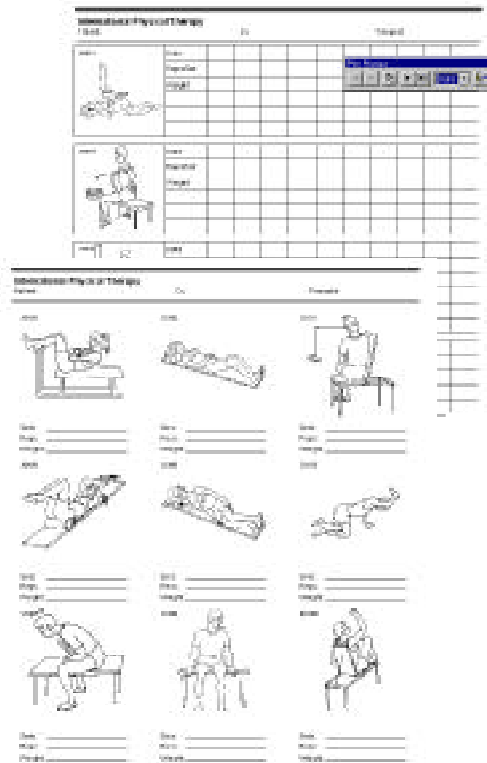
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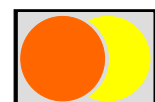
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