Biomechanics of the thorax – research evidence and clinical expertise

Diane Gail Lee

Diane Lee & Associates, Suite 102 15303 31st Avenue, Surrey, BC, Canada

Understanding the biomechanics of the thorax is critical for understanding its role in multiple conditions since the thorax is part of many integrated systems including the musculoskeletal, respiratory, cardiac, digestive and urogynecological. The thorax is also an integrated system within itself and an element of the whole body/person. Therefore, understanding the biomechanics of the thorax is fundamental to all forms of treatment for multiple conditions. The interpretation of movement examination findings depends on one's view of optimal biomechanics and the influential factors. This article will provide a synopsis of the current state of research evidence as well as observations from clinical experience pertaining to the biomechanics of the thorax in order to help clinicians organise this knowledge and facilitate evidence-based and informed management of the, often complex, patient with or without thoracic pain and impairment. The integrated systems model (ISM) will be introduced as a way to determine when the noted biomechanical findings are relevant to a patient's clinical presentation.

Keywords: Biomechanics of the thorax, Thorax, Biomechanics, Clinical expertise, Thoracic ring, Integrated Systems Model

Understanding the biomechanics of the thorax is critical for understanding its role in multiple conditions since the thorax is part of many integrated systems including the musculoskeletal, respiratory, cardiac, digestive and urogynecological. What is an integrated system? Integration has been defined as the linkage of differentiated elements of a system and is fundamental to health.¹ Understanding the relationships between, and within, integrated systems and the consequences of impaired function of one on another is complex. Multiple health practitioners specialise in varying aspects of thoracic health (orthopaedic physiotherapists, manual therapists, respiratory therapists and respirologists, massage therapists, cardiac physiotherapists and cardiologists, gastroenterologists, etc.) and treatment is often based on the practitioner's training and experience. The thorax is not only an integrated system within itself (i.e. comprises many differentiated yet linked parts) but also integrated as part of the whole body/person. Therefore, understanding the biomechanics of the thorax is fundamental to all forms of treatment for multiple conditions. The interpretation of movement examination findings depends on one's view of optimal biomechanics and the influential factors.

Surprisingly, there is limited research on the biomechanics of the thorax. This is perhaps due to the perception that it is a very stable structure or the belief that thoracic pain and impairment are not as prevalent as neck, shoulder or low back pain. Furthermore, the rib cage and the 13 joints per typical thoracic ring² (Fig. 1) pose significant methodological challenges for investigating segmental (inter and intra-ring) biomechanics. Many of the *ex vivo* studies investigating mobility and/or stability of a thoracic ring use cadaveric specimens without an intact rib cage, and while this is occasionally seen in clinical practice (rib removal), it is not the most common clinical presentation. Consequently, these studies are limited for application to clinical practice. Edmondston³ notes, 'A clearer understanding of thoracic spine mechanics has been achieved through the combined results of motion analysis studies of asymptomatic subjects in conjunction with clinical observation',³ page 55.

Evidence-based practice requires consideration of the best research evidence, clinical expertise and patient values.⁴ In other words, integration, the linkage of differentiated elements (research evidence, clinical expertise and patient values), is essential for best practice. An evidence-based practitioner:

- (a) Is informed of the relevant research evidence to the topic/patient
- (b) Has clinical expertise (skills to find relevant findings and clinical reasoning ability to interpret those findings)

Correspondence to: Diane Gail Lee, Diane Lee & Associates, Suite 102 15303 31st Avenue, Surrey, BC V3Z 6X2, Canada. Email: dianelee@dianelee.ca

Figure 1 A typical thoracic ring comprises two adjacent thoracic vertebrae, the associated costocartilage and ribs that articulate with both vertebra, the manubrium/sternum, and all the joints that connect these bones.²

- (c) Understands the patient's values and goals in order to provide meaningful treatment.

This article will provide a synopsis of the current state of research evidence as well as observations from clinical experience pertaining to the biomechanics of the thorax in order to help clinicians organise this knowledge and facilitate evidence-based and informed management of the, often complex, patient with or without thoracic pain and impairment. This article neither covers the biomechanics of static loading nor recent advances in motor control of the thorax.

Biomechanics of the Thorax – Research Evidence

Understanding research evidence and its applicability to a clinical situation is a critical component of evidence-based practice.⁴ Movement analysis of the thorax is an essential element of clinical examination, therefore an understanding of the biomechanics is needed. Furthermore, appropriate interpretation of the movement findings depends on the expectation of what should be occurring and the variables, or factors, influencing the motion. What does the research evidence tell us about the biomechanics of the thorax and can this research be clinically applied?

Segmental biomechanics of the thorax is difficult to investigate *in vivo* since no system is capable of measuring the various parameters of segmental motion. This includes motion between two thoracic rings (inter-ring) and within one ring (intra-ring). *In vivo* studies that record motion of one thoracic ring via markers on the spinous process and related ribs without considering the relative motion of this thoracic ring to the one above or below cannot determine inter-ring biomechanics, only regional conclusions can be drawn. Table 1 highlights the findings from six studies that investigated the regional biomechanics of the thorax under varying conditions.^{5–10} Willems *et al.*⁶ conclude that the

variability of coupling noted in the thorax ‘should warn clinicians against biasing selection of therapeutic movement techniques on purely theoretically derived patterns’⁶ page 315. Noting the wide variation in motion coupling in the thorax, Edmondston *et al.*⁷ suggest that clinicians ‘should not seek stereotypical patterns of coupled motion in the examination of spinal mobility’,⁷ page 198.

The biomechanical model of the thorax¹¹ was derived principally from the research of Panjabi *et al.*¹² and clinical observations.^{2,11,13} The functional spinal unit (FSU) was considered to be the most influential determinant for motion coupling.¹² In the thorax, the costovertebral and costotransverse joints were considered part of the FSU, but not the anterior portions of the ribs nor the anterior costochondral/sternochondral joints or the sternum; in other words, the thoracic ring was not intact. Clearly, this experimental *in vitro* situation is not representative of any patient seen in clinical practice so translating knowledge gained from this study has questionable validity. However, it is the only study that has identified contralateral transverse plane translation coupled with axial rotation. No *in vivo* studies have been able to measure the presence or absence of this coupled motion.

Molnár *et al.*¹⁴ found that the axis for thoracic rotation differed between the intact and non-intact thoracic ring and conclude that the intact thoracic ring has an effect on the biomechanics. This suggests that all investigations without intact ribs should be interpreted cautiously. Furthermore, Dickey & Kerr¹⁵ challenged the assumption that the mechanical behaviour of a single FSU is equivalent to the mechanics of these same segments in an intact multi-segmental spine.

In the literature review for this article, only one study was found that investigated *in vivo*, intact, thoracic ring biomechanics during one task, breathing.¹⁶ *In vivo* spiral computed tomography was used to determine the 3D motion of the ribs and related vertebrae at full inhalation, full exhalation and a point somewhere in-between. This study confirmed that ribs one to seven posteriorly rotate in full inhalation and anteriorly rotate in full exhalation. The mean helical axis for anterior and posterior rotation of the ribs was not oriented along the neck of the rib as previously described.¹⁷ Rather, the axis ran anterolateral and inferior approximately 45° to the mid-transverse plane. They also noted the presence of between-subject variations of the mean helical axis at the lower levels and postulated on the influence of different conditions (i.e. pulmonary, neuromusculoskeletal) on the kinematic parameters observed.

A systematic review investigated all studies from February 1965 to November 2006 that measured the

Table 1 Findings from six studies that investigated the regional biomechanics of the thorax under varying conditions^{5–10}

Authors	Method	Findings
Hsu <i>et al.</i> ⁵	Surface sensors spinous process C7, T12, S1, Mid-thigh Electromagnetic tracking of sensors during sagittal, coronal and transverse planes	Thorax contributed most to axial rotation, 60% of motion came from thorax
Willems <i>et al.</i> ⁶	Surface sensors spinous process T1, T4, T8 Electromagnetic tracking of sensors during movement in sagittal, coronal and transverse planes	Thorax contributed most to axial rotation, T4–8 produced 50% of total axial rotation Coupling of side-bending and axial rotation highly variable
Edmondston <i>et al.</i> ⁷	Reflective markers transverse processes T6 and 6th ribs Investigated influence of flexion/extension on amplitude and pattern of coupling of axial rotation	Pattern of coupling was variable and influenced by posture Postulate variations in anatomy, soft tissue extensibility an/or motor control strategies as influencing pattern variability
Edmondston <i>et al.</i> ⁸	Reflective markers spinous processes T1, T4, T8, T12 Lateral radiographs and photographic image analysis of thorax during bilateral arm elevation	Thorax extends, lower region > upper region
Theodoridis & Ruston ⁹	Electromagnetic tracking of T2–T7 during unilateral arm elevation	Variable coupling of lateral flexion and axial rotation, most coupled ipsilateral
Delphinus <i>et al.</i> ¹⁰	Reflective markers spinous processes C7, T10, suprasternal notch, xiphoid process, pelvis (ASIS & PSIS), greater trochanters 8 camera motion analysis system tracked 3D movements of thorax and pelvis during left and right axial rotation in neutral spine posture Four different trunk inclination positions with and without pelvic constraint	At 45° of anterior trunk inclination the thorax contributed 54% of the total trunk rotation Up to 30° of anterior trunk inclination the pelvis contributed more than 50% of the total trunk rotation

coupling behaviour of lateral flexion and axial rotation of the thoracic spine.¹⁸ Understanding the three-dimensional spine coupling characteristics as being important for treating patients with spinal pain was acknowledged. The methods of investigation were *in vivo*, *in vitro* or mathematical modelling of coupled motion in the thoracic spine. Fifty-six studies were considered and only eight were identified as having methods that analysed coupling motion of the thoracic spine. Six studies used trunk motion and two used upper extremity elevation to produce the coupling behaviour in the thoracic spine. Included in this review were studies pertaining to either cadaveric specimens with non-intact thoracic rings and mathematical modelling studies that did not consider the role of the ribs or sternum.^{12,19–21}

If these studies are eliminated due to their non-clinical applicability, only one study remains to consider; the study of Willems *et al.*⁶ However, this study did not investigate segmental, inter-ring biomechanics and therefore no conclusions can be made about segmental coupling for an intact thoracic ring for lateral flexion or axial rotation. Sizer *et al.*¹⁸ note that across all studies ‘variations were reported in side-bending and rotation initiation and no consistent pattern was observed when comparing *in vivo* versus *in vitro* findings’,¹⁸ page 396.

In addition, ‘*In vivo* studies are clinically applicable but lead to challenges in controlling extraneous variables that include motor and postural control, as well as tissue adaptation anatomical and circadian variability; applied preload forces the degree of thoracic kyphosis and scoliosis; and technical difficulty in measuring spinal coupling’,¹⁸ page 397. However, this is clinical reality and practitioners are expected to interpret movement behaviour with these variables *in situ*. ‘The lack of a common coupling pattern may merit individual clinical assessment for each patient examined’,¹⁸ page 397. How should clinicians interpret the biomechanical findings? What are the normal, or optimal, biomechanics for the thorax? What is abnormal? To date, the highest ranked level of evidence (a systematic review) does not provide clinicians with a biomechanical model against which to compare the patient’s movement results.

Masharawi *et al.*’s²² anatomical study provides some insight for the noted high variability in the biomechanics of the thorax across multiple studies. They measured the orientation of the facets of the zygapophyseal joints in 240 specimens from T1–L5; over 4080 vertebrae were measured. They found an asymmetric orientation (differences between the left and right sides) to be a ‘normal characteristic in the

thorax',²² page 762. Andriacchi *et al.*²³ suggest that the mechanical response of the costovertebral joint is strongly influenced by the joint's geometry, the same could be suggested for the zygapophyseal joints. Asymmetric anatomy may be a contributor to variability in motion coupling in the thorax.

Biomechanics of the Thorax – Clinical Expertise

In 1993, a clinical model of *in vivo* biomechanics of the thorax derived from clinical observations with consideration of the available evidence was proposed.¹¹ What follows is an update of this clinical model of *in vivo* biomechanics with consideration given to both the current research evidence and clinical experience gained since 1993. Table 2 outlines the terms and definitions used in this current clinical biomechanical model.

Forward bending of the trunk

Forward bending of the trunk can occur using a 'hip strategy' in which either minimal movement occurs in the thoracolumbar spine or the thoracolumbar spine extends, a 'spinal strategy', in which most movement occurs in the spine, or a combination of both. In a combination strategy, the thorax anteriorly tilts, the amount of which varies between individuals and between the thoracic rings, the lumbar spine flexes and the pelvis anteriorly tilts relative to the femurs (Fig. 2). The least amount of motion appears to occur in the mid-thoracic region. The following biomechanics are proposed to be optimal for each element comprising the thoracic ring when the ring anteriorly tilts in forward bending of the trunk (Fig. 3):

1. Spinal biomechanics:

- a. Osteokinematics: the superior vertebra flexes relative to the inferior vertebra (all four regions). In the vertebrosteral (VS – thoracic rings 3–6) and vertebrochondral (VC – thoracic rings 7–10)

regions of the thorax the superior articular process is inclined slightly anterior in the coronal plane;²² therefore, a small amount of anterior translation of the superior vertebra occurs in conjunction with flexion.

- b. Arthrokinematics: the inferior articular process of the superior vertebra glides superiorly and slightly anterior (following the joint's orientation), which may be variable both regionally and between sides of the same segment.²²
2. Costal biomechanics:
- a. Osteokinematics: the left and right ribs of the thoracic ring should anteriorly rotate relative to their starting position. The axis for this motion has not been determined.
 - b. Arthrokinematics: VM and VS regions – the shape of the costotransverse joint is concavoconvex in both the VM and VS regions; therefore, if the rib anteriorly rotates relative to the vertebra of the same number, the convex facet on the rib glides superiorly and rolls anteriorly relative to the facet on the transverse process. However, this depends on the movement strategy (motor control) and any additional forces (force closure) potentially compressing the joint (relative flexibility). In the VC region, the shape of the costotransverse joint is planar and the orientation of the joint is in the anterolateroinferior (ALI)/posteromediosuperior (PMS) plane (Fig. 4). Thus, anterior rotation of ribs 7–10 relative to the transverse process requires a PMS glide. Alternately, if the chosen motor control strategy significantly compresses the costotransverse joints, no motion may occur between the ribs and the relevant transverse process when the thoracic ring anteriorly tilts during forward bending of the trunk.

Backward bending of the trunk

Backward bending of the trunk can occur using a 'hip strategy' in which minimal movement occurs in

Table 2 Terms used in the clinical biomechanical model for the thorax²

Term	Definition
Regions of the thorax	Vertebromanubrial – includes the first two thoracic vertebrae, ribs one and two and the manubrium. Vertebrosteral – includes T3 to T6, the third to sixth ribs and the sternum. Vertebrochondral – includes T7 – T10 together with the 7 th – 10 th ribs. Thoracolumbar – includes the T11 and T12 vertebrae and the eleventh and twelfth ribs.
Osteokinematics	Study of the motion of bones regardless of the motion of the associated joints. Angular motions are named according to the axis about which they rotate: Coronal axis: flexion/extension Paracoronal axis: anterior/posterior rotation Sagittal axis: Side-bending Vertical axis: Axial rotation Linear motions are named according to the axis along which they translate: Coronal axis: mediolateral translation Paracoronal axis: anteromedial/posterolateral translation Vertical axis: distraction/compression Sagittal axis: anteroposterior translation
Arthrokinematics	Study of the motion of joints regardless of the motion of the bones. Motions are named according to the direction the joint surfaces glide relative to each other.
Coupling	Coupling biomechanics is the rotation or translation of a vertebral body about or along one axis that is consistently associated with the main rotation or translation on about another axis.
Translation	When movement is such that all particles in the body at a given time have the same direction of motion relative to a fixed coordinate system.
Rotation	Rotation occurs as a spinning or angular displacement of the vertebral body around a particular axis of rotation.

Figure 2 A combination strategy for forward bending. The thoracolumbar spine flexes (least amount of movement appears to be in the mid-thorax), the lumbar spine flexes and the pelvis anteriorly tilts (hips flex).

Figure 3 Osteokinematic and arthrokinematic motion of the ribs and vertebrae of the typical thoracic rings 3–6 when the ring anteriorly tilts. The large yellow arrows indicate the direction of the osteokinematic motion (ribs anteriorly rotate, vertebrae flex), the small arrow on the tubercle of the rib indicates the direction of the arthrokinematic glide at the costotransverse joint (superior with an anterior roll). The white space on the anterior aspect of the inferior facet of the superior vertebra denotes the relative superior glide that occurs during this motion.

the thoracolumbar spine, a ‘spinal strategy’, in which most movement occurs in the thoracolumbar spine or a combination of both. In a combination strategy, the thorax posteriorly tilts, the amount of which varies between individuals and between the thoracic rings, the lumbar spine extends and the pelvis posteriorly

Figure 4 The orientation of the costotransverse joint in the vertebrochondral region (rings 7–10) is in the PMS/ALI plane thus anterior and posterior rotation of the associated rib requires a PMS (for anterior rotation) and an ALI (for posterior rotation) glide at this joint.

tilts relative to the femurs (Fig. 5). The least amount of motion appears to be in the VS region. The following biomechanics are proposed to be optimal for each element comprising the thoracic ring when the ring posteriorly tilts in backward bending of the trunk (Fig. 6):

1. Spinal biomechanics:

- Osteokinematics:** the superior vertebra extends relative to the inferior vertebra (all four regions). In the VS and VC regions of the thorax, the superior articular process is inclined slightly anterior in the coronal plane; therefore, a small amount of posterior translation of the superior vertebra occurs in conjunction with extension.
- Arthrokinematics:** the inferior articular process of the superior vertebra should glide inferiorly and slightly posterior following the joint's orientation, which may be variable both regionally and between sides of the same segment.

2. Costal biomechanics:

- Osteokinematics:** the left and right ribs posteriorly rotate relative to their starting position (VM, VS and VC regions). The axis for this motion has not been determined.
- Arthrokinematics:** VM and VS – the shape of the costotransverse joint is concavoconvex in both the VM and VS regions; therefore, if the rib posteriorly rotates relative to the vertebra of the same number, the convex facet on the rib glides inferiorly and rolls posteriorly relative to the facet on the transverse process. However, this depends on the movement strategy (motor control) and any additional forces (force closure) potentially compressing the joint (relative flexibility). In the VC region, the shape of the costotransverse joint is planar and the orientation of the joint is in the ALI/PMS plane (Fig. 4). Thus, posterior rotation of ribs 7–10 relative to the vertebra requires an ALI glide. Alternately, if the chosen motor control strategy significantly compresses the costotransverse joints, no motion may occur between the ribs and the relevant vertebra when the thoracic ring posteriorly tilts during backward bending of the trunk.

Figure 5 A combination strategy for backward bending. The thoracolumbar spine extends (least amount of movement appears to be in the mid-thorax), lumbar spine extends and the pelvis posteriorly tilts (hips extend).

Figure 6 Osteokinematic and arthrokinematic motion of the ribs and vertebrae of the typical thoracic rings 3–6 when the ring posteriorly tilts. The large yellow arrows indicate the direction of the osteokinematic motion (ribs posteriorly rotate, vertebrae extend); the small arrow on the tubercle of the rib indicates the direction of the arthrokinematic glide at the costotransverse joint (inferior with a posterior roll). Note the absence of the white space on the anterior aspect of the inferior facet of the superior vertebra – the arthrokinematic glide is inferior during this motion.

Given both regional and side-to-side variations in anatomy, asymmetry in the amplitude of motion should not be considered pathognomonic of non-optimal biomechanics for forward or backward bending. Other clinical considerations are required to determine the relevance

of asymmetry (see the Integrated Systems Model below for further discussion).

Side-bending of the trunk

Side-bending of the trunk produces segmental lateral flexion of the thorax at all regions and a variety of coupling possibilities. Overall, a gentle even curve convex on the opposite side of the side-bending should occur. Once side-bent, anterior/posterior tilting of the thorax becomes more limited. The following biomechanics are proposed to be optimal for each element comprising the thoracic ring when the ring laterally flexes/rotates in side-bending of the trunk (Fig. 7):

1. Spinal biomechanics:

- a. Osteokinematics: the superior vertebra should laterally flex relative to the inferior vertebra (all four regions) and rotation may be segmentally coupled in an ipsilateral or contralateral direction. If the superior vertebra is free to follow the orientation of the zygapophyseal joints then the pattern is often ipsilateral.
- b. Arthrokinematics: during right lateral flexion the inferior articular process of the superior vertebra glides inferiorly (and slightly posteriorly) on the right and superiorly (and slightly anteriorly) on the left. The anteroposterior translation that couples with the superoinferior glide likely depends on the amplitude, direction and symmetry of inclination of the facets in the coronal plane.

2. Costal biomechanics:

- a. Osteokinematics: during right side-bending, the ribs approximate on the right and separate on the left at the VM, VS and VC regions. What happens at the end of the range depends on the motor control strategy chosen for the task and the degree of articular compression (stiffness) that occurs. In the VM and VS regions, *if* the ribs stop moving and the thoracic spine is still able to laterally flex to the right, the right

Figure 7 Osteokinematic and arthrokinematic motion of the ribs and vertebrae of the typical thoracic rings 7–10 when the ring laterally flexes to the right. The yellow arrow indicates the direction of lateral flexion and the red arrows denote the relative glide of the ribs if the inferior vertebra is free to continue to laterally flex after the ribs stop moving. The vertebra is the moving bone and glides ALI on the right (rib goes PMS) and PMS on the left (rib goes ALI).

transverse process will glide inferiorly and roll around the convex articular surface of the right rib while the left transverse process will glide superiorly and roll around the convex articular surface of the left rib (arthrokinematics) facilitating more right (ipsilateral) rotation of the superior vertebra *in space*. However, the resultant *segmental coupling* of spinal osteokinematics depends on what the inferior vertebra does (relative biomechanics). Rotation of the superior vertebra will be contralateral to the direction of lateral flexion if the inferior vertebra rotates further to the right (in space). Considering the anatomy of the costovertebral joint, it is likely that the head of the rib would prevent end-range segmental ipsilateral coupling in lateral flexion. In the VC region, the orientation and shape of the costotransverse joints result in the right transverse process gliding ALI and the left gliding PMS during right lateral flexion. Segmental coupling for rotation is variable.

Axial rotation of the trunk

Axial rotation of the thorax is an integral component of many functional tasks and thus a critical movement to examine and interpret. Overall, a gentle even curve convex on the opposite side of the rotation should occur. The following biomechanics are proposed to be optimal for each element comprising the thoracic ring when the ring rotates in axial rotation of the trunk (Fig. 8):

1. Spinal biomechanics:
 - a. Osteokinematics: the superior vertebra rotates in the same direction as the axial rotation (VM, VS VC regions). If the superior vertebra is free to follow the orientation of the zygapophyseal joints then the pattern of coupling with lateral flexion is ipsilateral. There is also a slight contralateral translation in the transverse plane of the superior vertebra relative to the inferior.
 - b. Arthrokinematics: during right axial rotation, the inferior articular process of the superior vertebra glides inferiorly (and slightly posteriorly) on the right and superiorly (and slightly anteriorly) on the left. The anteroposterior translation that couples with the superoinferior glide likely depends on the amplitude, direction and symmetry of inclination of the facets in the coronal plane.
2. Costal biomechanics:
 - a. Osteokinematics: during right axial rotation, the right rib posteriorly rotates and the left rib anteriorly rotates both in space and relative to the vertebrae that comprise the thoracic ring. In addition, in the VS and VC regions (thoracic rings 3–10) there is a slight contralateral transverse plane translation that occurs between the ribs and their relative transverse processes. A suitable metaphor for this motion is the linear translation that occurs when a screw is rotated into wood. This motion follows the noted contralateral transverse plane translation of the relevant thoracic vertebra. The second thoracic ring is variable with respect to this

Figure 8 Osteokinematic and arthrokinematic motion of the ribs and vertebrae of the typical thoracic rings 3–6 when the ring rotates to the right. The yellow arrows on the green ribbon denote the small contralateral translation that occurs between the superior vertebra/left and right ribs and the inferior vertebra. The red arrows indicate the anterior (left) and posterior (right) rotation of the ribs that occur in conjunction with the contralateral translation during right axial rotation.

transverse plane translation. The rings that are atypical (1, 11, 12) do not appear to translate in the transverse plane during axial rotation. The only study to report on this motion is an *in vitro* one done on non-intact thoracic rings.¹² The motion is small, yet palpable.^{2,11}

- b. Arthrokinematics: costotransverse joints of thoracic rings 1–6: during right axial rotation, the convex articular surface of the right rib glides inferiorly and rolls posteriorly while the left rib glides superiorly and rolls anteriorly relative to the transverse process. Costotransverse joints of thoracic rings 7–10: during right axial rotation, the planar articular surface of the right rib glides ALI while the left rib glides posteromediosuperiorly relative to the transverse process. The coupled contralateral (left) transverse plane translation that occurs from rings (2), 3–10 results in a simultaneous anteromedial glide of the right rib (relative to its transverse process) and a posterolateral glide of the left (imagine the turning screw).

Bilateral and unilateral arm elevation

Consistent with the research,⁸ the integrated thorax (all regions) extends when both arms are elevated overhead. During unilateral arm elevation the thorax rotates and laterally flexes towards the side of the elevating arm. The variability of coupling noted by Theodoridis & Ruston⁹ is seen clinically and often reflects variations in motor control strategies for performance of this task.

Assessment of thoracic inter-ring and intra-ring alignment, biomechanics and control during movement analysis of a patient's meaningful task are key components of the Integrated Systems Model (ISM),²⁴ a clinical reasoning, evidence-based approach that helps to understand the clinical relevance of the noted findings.

The Integrated Systems Model – A Framework to Organise Knowledge

The ISM is a framework, not a classification system, to help clinicians organise knowledge and develop clinical reasoning to facilitate wise decisions for treatment. The ISM approach is applicable to disability with or without pain (peripheral or centrally mediated) of any duration (acute or chronic) and is centred on the patient's values and goals, a key component of evidence-based practice. The assessment is meaningful to the patient's story and is not protocol-driven or based on clinical guidelines or prediction rules for regional pain. A key feature of this whole body/person approach is *Finding the Primary Driver*. In short, this involves understanding the relationships between, and within, multiple regions of the whole body and how impairments in one region can impact the other. Specific tests are used to determine sites of non-optimal alignment, biomechanics and control [defined as failed load transfer (FLT)] during analysis of a task that is meaningful to their story/complaint (meaningful task analysis). Subsequently, the timing of FLT (which site fails first, second, third, etc.), as well as the impact of providing manual and/or verbal cues to correct one site on another, is noted. Clinical reasoning of the various results determines the site of the primary driver, or the primary region of the body, that if corrected will have a significant and positive impact on the function of the whole body/person. Sometimes, two areas of the body require intervention (co-drivers) and sometimes one area requires most treatment (primary) while another requires some attention for the best outcome (secondary driver).

Further tests of specific systems²⁵ (e.g. articular, neural, myofascial, visceral) then determine the underlying impairment causing the non-optimal alignment, biomechanics and/or control of the driver(s) for the specific task being assessed. Once the impaired system has been determined, specific techniques and training for release, alignment, control and integration into movement (including strength and conditioning) can be implemented to improve the function of the driver(s) and thus impact the function of the whole body/person.^{26–28}

Let us apply the principles of the ISM approach to the biomechanical analysis of the thorax with a clinical example. In Fig. 9A, notice the right side-bending curve in the VS region of this young woman's thorax. Her meaningful complaint is neck pain associated with restricted left head and neck rotation. The VS thoracic rings appear compressed on the right and separated on the left when palpated in the mid-axillary line and one thoracic ring (fourth) appears to be translated to the left (consistent with the appearance of the right

Figure 9 (A) Note the side bending of the vertebrosternal region of this thorax and the resultant position of the shoulder girdles (right one is depressed). My left and right hand are palpating the left and right fourth ribs in the mid-axillary line; they are clearly not on the same transverse plane. The fourth thoracic ring is translated to the left and rotated to the right. (B) Left head/neck/thorax rotation is limited to the left perhaps by the inability of the fourth thoracic ring to translate to the right and rotate to the left. Non-optimal biomechanics of the fourth thoracic ring are felt when she attempts to rotate further to the left and her neck pain is reproduced.

Figure 10 (A) A manual correction of the fourth thoracic ring alignment²⁹ immediately changes the resting position of both shoulder girdles and straightens the side bending curve in the vertebromanubrial and vertebrosteral regions of her thorax. **(B)** Subsequent assessment of her meaningful task (left head/neck/thorax rotation) reveals an immediate improvement of the neck and upper thorax biomechanics and reduction in neck pain. Further assessment is required to determine the underlying system impairment (neural, articular, myofascial, visceral) that is causing the non-optimal alignment and biomechanics for this task.

side-bent/rotated VS curve). During left head and neck rotation (Fig. 9B), notice the amplitude of motion, the position of her shoulder girdles and the persistence of the right side-bent/rotated VS curve. What is felt in the mid-axillary line is an increase in the *left* translation of the fourth thoracic ring.²⁹ According to the biomechanical model proposed here, left translation of a thoracic ring occurs in conjunction with right axial rotation (Fig. 8). Right axial rotation of the fourth thoracic ring would oppose, or potentially limit, the ability of the head/neck and upper thorax to rotate to the left, the desired motion for this task. Is there any relevance to this clinical finding (i.e. the left translated fourth thoracic ring)? In the ISM approach, the next step is to provide 'a correction',²⁹ which in this case means active assistance for left axial rotation of the fourth thoracic ring. Since an intact thoracic ring is an integrated unit, facilitating posterior rotation of the left rib while simultaneously distracting the fourth thoracic ring from the fifth (decompress the segment) will create an entire biomechanical ring response as long as the joints are able to move and the muscles respond correctly to this sensory input. Note the difference in the alignment of the VS region and the shoulder girdles when this biomechanical correction of the fourth thoracic ring is applied (Fig. 10A) and the immediate improvement in the amplitude of head/neck/upper thorax (VM) rotation (Fig. 10B). This is not a complete restoration of optimal biomechanics since the VS curve has only been restored to neutral with this correction; however, the improvement in performance of the task and reduction in symptoms suggest that treating the fourth thoracic ring with any technique to improve inter-ring and intra-ring left thoracic rotation would be beneficial for this patient. If there had been no improvement in the performance of the task or the symptoms and/or performance had been made worse, then this finding would suggest that the left lateral translation (right axial rotation) of the fourth thoracic ring was not the best place to intervene. It may be compensating for a different impairment elsewhere or it may be a structural/anatomical irrelevant finding. Go look elsewhere for something that when corrected (alignment, biomechanics and/or control) improves both the performance of the meaningful task and reduces the symptom experience.

Conclusion

When the proposed biomechanical model of the thorax is used in conjunction with the principles of the ISM, the relevant clinical findings can be determined. Since the thorax is integrated with the entire body, biomechanical impairments of alignment, movement and control can impact body regions far removed from the thorax. Poor biomechanics of the thorax are often implicated in multiple conditions across a wide variety of populations; optimal

thoracic function is paramount for good health.

In the opening keynote address of the 2012 IFOMPT conference in Quebec, Professor Gwen Jull said: 'The future of physiotherapy continues with an informed clinically reasoned assessment approach to direct management of the individual patient.' Sackett *et al.* note that 'External clinical evidence can inform, but can never replace individual clinical expertise, and it is this expertise that decides whether the external evidence applies to the patient at all, and if so, how it should be integrated into a clinical decision'.⁴

In short, regardless of what you believe needs to be done, the individual knows best and when the appropriate change(s) in alignment, biomechanics and/or control is/are provided (to the thorax, pelvis, foot, hip, etc.), there is an immediate improvement in both performance and the experience of the meaningful task. Clinical reasoning using models such as the ISM coupled with an informed understanding of the highly variable biomechanics of the thorax is the evidence-based way forward for direct management of the individual patient.

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Nothing develops in isolation or a vacuum, most concepts and ideas come from collaboration. The clinical biomechanical model of the thorax was originally developed in conjunction with the associates at Delta Orthopaedic Physiotherapy Clinic between 1988 and 1993. Not much has changed except for the understanding that not all joint restrictions are due to articular system impairments and that 'manual correction of a thoracic ring' (Linda-Joy Lee) can differentiate neural system impairments from articular ones. The ISM was co-developed with Linda-Joy Lee (1999–2013) and remains the clinical reasoning approach I use, and teach, to help clinicians identify and treat relevant movement impairments. I would like to acknowledge Linda-Joy Lee for the co-development of the ISM as well as my current team of associates and education assistants Rachael Corbett, Cathy Rogers, Nicole McVarish and Tamarah Nerreter who continue to support and help me inform clinicians of this evidence-based approach, part of which requires an understanding of the biomechanics of the thorax.

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