Multisystem Clinical Implications of Impaired Breathing Mechanics and Postural Control

Mary Massery

KEY TERMS

Abnormal or compensatory breathing patterns
Abdominal binder
Breathing mechanics
Cardiac mechanics
Gastrointestinal impairments
Gravitational influence on physical development
Integumentary impairments
Internal organs
Multisystem interactions
Musculoskeletal impairments
Neuromuscular impairments
Normal and abnormal chest wall development
Paradoxical breathing
Pelvic floor
Postural control
Reflux
Sandifer's syndrome
Scoliosis
Soda Can Model of respiratory and postural control
Spinal cord injury
Vocal folds/glottis

CHAPTER OUTLINE

Breathing: A Three-Dimensional Gravity-Dependent Activity 634
Planes of Ventilation and Gravitational Influence 634
Effects of Gravity on Normal and Abnormal Chest Wall Development 634
Influence of Multisystem Interactions on Motor Performance: Relationship Between Respiratory and Postural Control 637
Soda Can Model of Respiratory and Postural Control 638
Soda Can Model Summary 641
Compensatory Breathing Patterns Associated with Insufficient Muscular Support 642
Paradoxical Breathing 642
Diaphragm and Upper Accessory Muscles Only (Paralyzed or Nonfunctional Intercostal Muscles) 643
Upper Accessory Muscles Only 643
Asymmetrical Breathing 643
Lateral or Gravity-Eliminated Breathing 644
Shallow Breathing 644
Application of the Soda Can Model to a Clinical Example 644
Multisystem Evaluation, Examination, and Intervention 644
Application 649
Summary 651
Review Questions 651
References 651

The cardiovascular and pulmonary systems provide both physiological support (oxygen delivery) (see Chapters 2 and 4) as well as a mechanical support (respiratory and trunk muscle control) for movement. This chapter focuses on breathing mechanics and their interactions with other organ systems in both health and dysfunction. Its three main premises are:

1. Breathing is a three-dimensional motor task that is influenced by gravity in the three planes of motion.
2. Breathing is influenced by multisystem interactions that simultaneously support respiratory and postural control during motor tasks.
3. The mechanics of breathing influence both health and motor performance outcomes related to participation.

The four motor impairment categories identified in the *Guide to Physical Therapist Practice*, second edition, are incorporated into this chapter.[1] A fifth category, the internal organs, has been added (Box 39-1). In addition to addressing the impact of these impairment categories on health and motor performance from a ventilatory perspective, we present a method to cross-reference impairment-based findings with functional limitations. Six common functional tasks that require the integration of breathing and movement are shown in Box 39-2. Children and adults with multiple physical challenges are patients in whom the interaction between respiratory control and postural control is particularly relevant.

Box 39-1 Motor Impairment Categories

Neuromuscular system
Musculoskeletal system
Integumentary system
Cardiovascular and pulmonary systems
Internal organs, especially the gastrointestinal system

Modified from American Physical Therapy Association: Guide to physical therapist practice, ed 2, *Physical Therapy* 81:29,133, 2001.

Box 39-2 Daily Tasks That Require the Integration of Respiratory and Postural Demands of the Trunk for Function

Breathing
Coughing
Sleeping
Eating
Talking
Moving

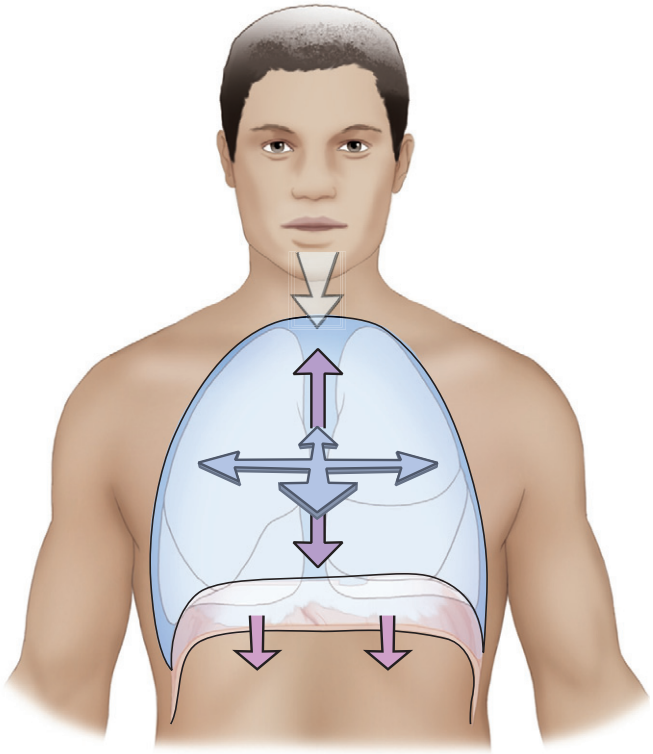


Fig. 39-1 Planes of respiration: anterior-posterior, inferior-superior, and lateral.

The role of multisystem interaction in effective breathing and postural control is an emerging field; hence it lacks rigorous evidence from experimental evaluation. Nonetheless, the physiologic evidence supporting the interactions among systems and their impact on breathing and posture (see Chapter 6) is compelling and sufficient to inform contemporary approaches to patient care in physical therapy practice. As an area of research, multisystem interaction represents a relatively new frontier that could have far-reaching implications for research in other physical therapy areas with respect to assessment, intervention, and evaluation.

Breathing: A Three-Dimensional Gravity-Dependent Activity

Planes of Ventilation and Gravitational Influence

Ventilation is a three-dimensional activity. With each breath, the chest wall expands in the anterior-posterior plane, the inferior-superior plane, and the medial-lateral plane (Figure 39-1). The muscles that support breathing are resisted by gravity in one direction, assisted by gravity in another direction, and relatively unaffected in other directions. When a person is upright, superior expansion of the chest wall is resisted by gravity while inferior expansion is assisted, and other movements of the chest wall (anterior, posterior, and lateral expansion) are relatively unaffected by gravity. The adverse effects of gravity are counteracted by muscles that can function effectively in the presence of gravitational force. If the respiratory muscles become dysfunctional due to weakness, paralysis, or fatigue; or pathological conditions, the patient may no longer breathe effectively within gravity's influence.[2,3] Further, the impact of posture on breathing mechanics, as well as on cardiovascular function, has been well documented (see Chapter 20).[4] Therefore, when physical therapists are positioning patients with impaired breathing mechanics or posture, they need to consider how gravity can affect the muscles that support breathing and posture in each body position, as well as how it affects oxygen transport overall.

Effects of Gravity on Normal and Abnormal Chest Wall Development

Gravitational force is crucial in the normal development of the skeleton. Typically developing infants move freely in and out of a range of body positions (prone, hands and knees, and standing), allowing gravity to alternately assist or resist their movements. Moving through these positions, the infant strengthens muscle groups and learns to interact with the gravitational force in his or her physical environment and compensate as needed.[5] The development of the bones, muscles, and joints that constitute the trunk is influenced by genetic factors and movements performed in a gravitational field. Infants with limited ability to move and counteract gravity develop malaligned joints and impaired muscle support that, in turn, impair breathing mechanics, or vice versa.[6-8] Cerebral palsy, spinal muscle atrophy, stroke, head trauma, and spinal cord injury are conditions that can cause such muscle imbalance in children.[3] Weakness or fatigue of the trunk muscles can result from conditions outside the neuromuscular system[9] (for example, oxygen transport deficits from bronchopulmonary dysplasia and congenital heart defects and nutrition-related deficits such as gastroesophageal reflux and malabsorption; see Chapters 6 and 32). Such symptoms can impair breathing mechanics, as well as muscle tone

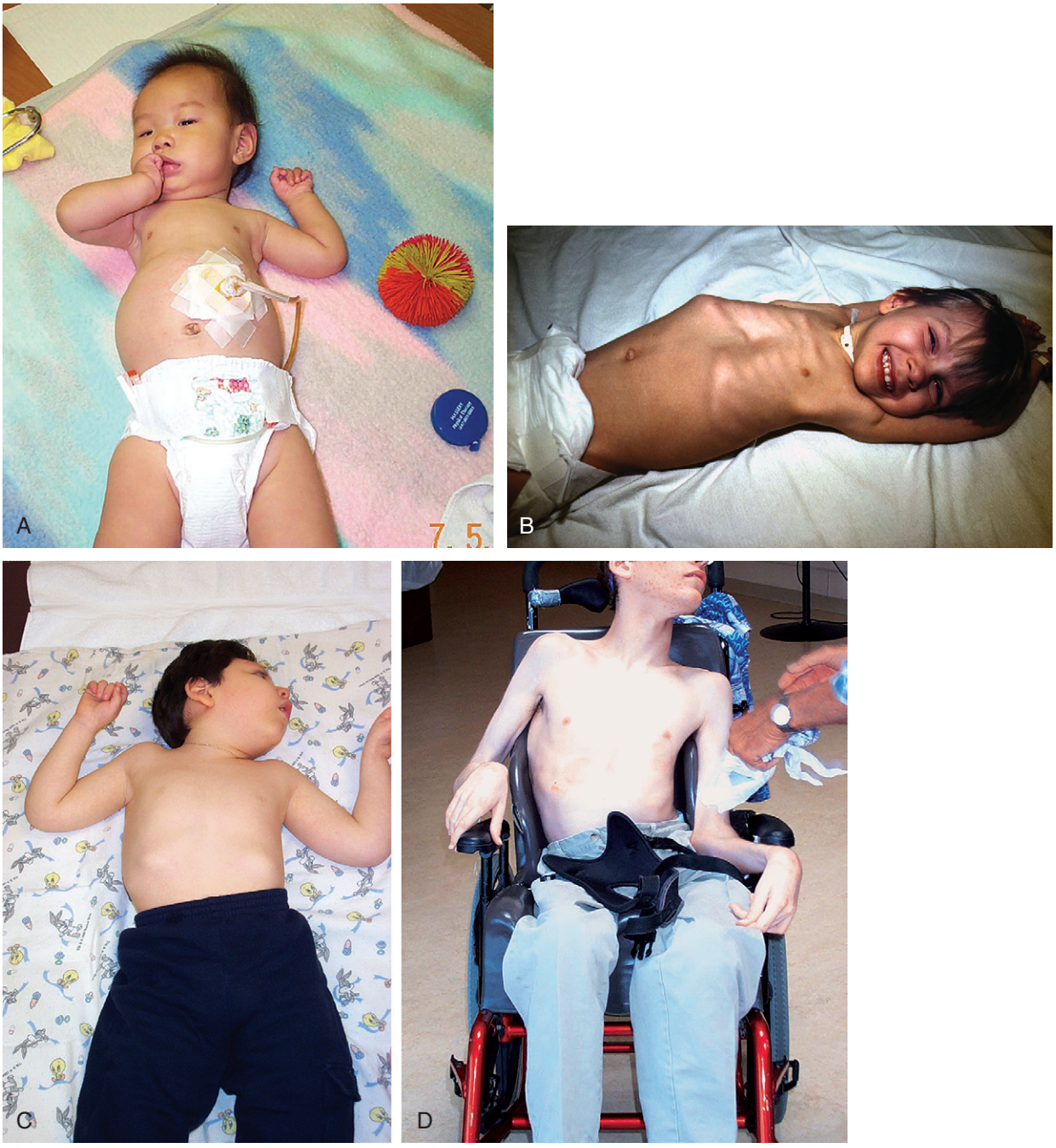


Fig. 39-2 A, Caitlin, six months of age. Caitlin has spinal muscle atrophy, type I. Note persistent immature triangular shaping of chest wall secondary to pronounced muscle weakness and an inability to counteract gravity effectively. **B,** Melissa, three-and-a-half years of age. Melissa has a C5 complete spinal cord injury due to birth trauma. Melissa's chest wall has become more deformed than Caitlin's chest wall due to the prolonged exposure to the severe muscle imbalance of the respiratory muscles within gravity's constant influence. Note the marked pectus excavatum and anteriorly flared ribs in supine. **C,** Carlos, 5 years of age and **D,** Kevin, 17 years of age. Both have spastic cerebral palsy. Note the lateral flaring of the lower ribcage, the asymmetry of the trunk, and the flattening of the entire anterior ribcage, all of which are more noticeable in the older child.

(as in hypertonicity or hypotonicity), and can contribute to deficits in motor planning and learning.[10]

Children who have impaired breathing mechanics and are recumbent for prolonged periods are exposed to abnormal gravitational stress. Over time, this leads to pathological changes and deformities such as retention of the primitive triangular shape of the newborn chest wall (Figure 39-2, *A*). In some cases, the child's diaphragm remains functional in the presence of weak or paralyzed abdominal and intercostal muscles. In turn, this can affect skeletal development (Figure 39-2, *B*). Pronounced imbalance of the thoracic muscles can result in chest wall deformity, compromising the child's ability to meet his or her ventilatory needs. Musculoskeletal abnormalities include anteriorly flared lower ribs, dynamic pectus deformity (most often, pectus excavatum; less often, pectus carinatum), laterally flared ribs, and chest wall asymmetry

Fig. 39-3 A and **B,** Chest wall of a newborn. Note triangular shape, short neck, narrow and flat upper thorax, round barreled lower thorax. Muscle tone is primarily flexion and breathing is primarily diaphragmatic and in one plane: inferior.

(Figure 39-2, *B, C, D*).[6,8,11] These deformities have varying impact on ventilation depending on the gravitational consequences of each position.

Understanding chest wall development in typically healthy children is essential for the physical therapist to assess chest wall deformities and their impact on oxygen transport.[11] Chapter 37 describes normal growth and development of the cardiovascular and pulmonary systems during infancy and childhood. The present chapter takes this information a step further, and considers the impact of musculoskeletal and neuromuscular impairments on typical childhood development. Initially the newborn's chest wall is triangular: narrow and flat in the upper portion and wider and rounded in the lower portion (Figure 39-3). The infant's short neck reduces the effectiveness of the upper accessory muscles as ventilatory muscles. The infant's arms tend to be flexed and adducted across the chest wall, hampering lateral or anterior movement of the chest wall. The infant, largely a diaphragmatic breather, shows disproportionate development of the lower chest wall, which promotes a triangular shape of the ribcage. Newborns breathe primarily in a single plane (inferior), rather than in three planes apparent in adults.

From 3 to 6 months of age, the infant develops more trunk extension tone and spends more time on his or her elbows in prone. The baby begins to reach with the arms into the environment. This facilitates development of the anterior upper chest wall. Continuous stretching and upper extremity weight bearing helps to expand the anterior upper chest wall both anteriorly and laterally, while increasing posterior stabilization.[5] An increase in the strength of the intercostal muscles and pectoralis muscles improves the infant's ability to counteract gravity exerted on the anterior upper chest wall in the supine position, leading to the development of a slight convex configuration of the area and a rectangular shaping of the thorax from the frontal plane (Figure 39-4). The baby begins to breathe more effectively in multiple planes as the muscles' length-tension relationships become more efficient.

The next step in development occurs when the child assumes erect body positions independently (i.e., sitting, kneeling, and standing). Until this time, the ribs are aligned relatively horizontally, with narrow intercostal spacing (Figure 39-3). The newborn's chest wall accounts for about one-third of the trunk cavity. As the child progressively moves against gravity, the ribs, with the aid of the abdominal muscles, rotate downward (more so in the longer lower ribs), creating the sharp angle of the ribs (Figure 39-5). This elongates the ribcage until it eventually occupies over half of the trunk cavity (Figure 39-6). Chest x-rays of newborns and adults, as

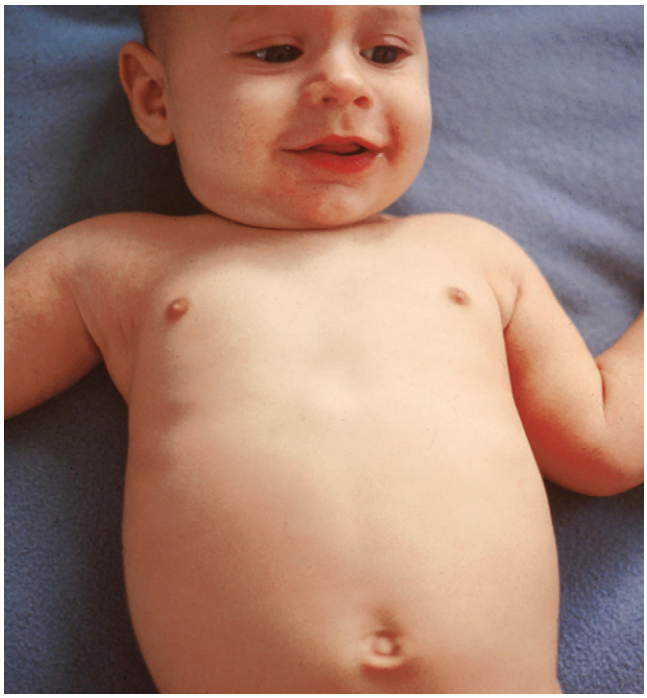


Fig. 39-4 Infant chest wall at 3 to 6 months of age. Increased upper thorax width. More convex shaping of entire chest wall occurs as antigravity movements are becoming possible. Note the short neck and two functionally separate chambers: thorax and abdomen.

Fig. 39-5 Infant chest wall at 6 to 12 months of age. The infant spends more time upright. The activation of abdominal muscles, gravity's influence, and increased postural demands result in a more elongated chest wall, wider rib spacing, and increased intercostal muscle activation, as well as a functional interface of the ribcage onto the abdomen with the abdominal and intercostal muscles. This improves both the respiratory dynamics by giving more external support to the diaphragm at the mid-trunk level and the postural stabilization potential needed for more complex motor tasks. Note that the base of the ribcage is no longer barrel-shaped as it is in the newborn.

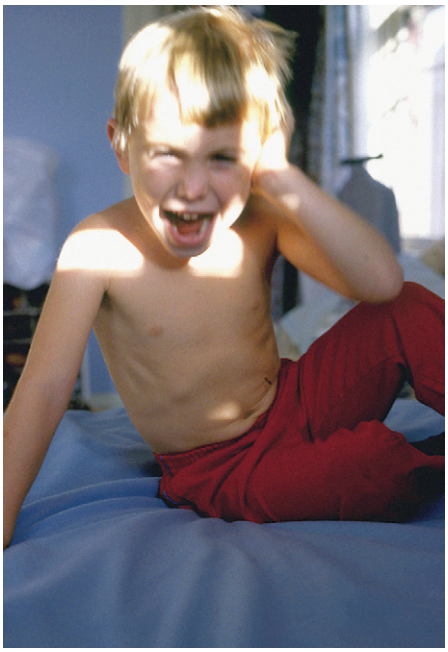


Fig. 39-6 A 4-year-old boy. Note the elongated chest wall, which occupies more than half of the trunk space, the wide intercostal spacing, the effective muscle stabilization of the lower ribcage with the abdominal muscles, the rectangular shaping of the chest wall from a frontal view, and the elliptical shaping of the chest wall from a transverse view.

Table 39-1 Typical Chest Wall Development from Infant to Adulthood

Chest Wall Components	Infant	Adult
Size	Thorax occupies one third thoracic cavity	Thorax occupies more than half thoracic cavity
Shape	Triangular frontal plane, circular anterior-posterior plane	Rectangular frontal plane, elliptical anterior-posterior plane
Upper thoracic	Narrow, flat apex	Wide, convex apex
Lower thoracic	Circular, flared lower ribs	Elliptical, lower ribs integrated with abdominals
Ribs	Evenly horizontal	Rotated downward, especially inferiorly
Intercostal spacing	Narrow, limits movement of thoracic spine and cavity	Wide, allows for individual movement of ribs and spine
Diaphragm	Adequate, minimal dome shape	Adequate, large dome shape
Accessory muscles	Nonfunctional	Functional

well as pictures of infants, illustrate these developmental trends (Figure 39-7, *A, B*); details are further summarized in Table 39-1.

Optimum respiratory function cannot be expected in a person with an underdeveloped or deformed chest wall, spine, or both.[3] As long as the condition that caused the trunk muscle imbalance persists, regardless of whether that deficit was a neuromuscular disorder or an impairment in another motor impairment category (see Box 39-1), the chest wall and spine will likely develop atypically.

Strategies to optimize trunk development include:

- Frequent body position changes
- Management of adverse neuromuscular tone
- Facilitation of weakened chest wall muscles
- Promotion of optimal breathing patterns
- Incorporation of ventilatory strategies with movement
- The alignment of physical therapy goals with the child's development and medical program

Influence of Multisystem Interactions on Motor Performance: Relationship Between Respiratory and Postural Control

Normal human movement reflects the interactions of multiple organ systems. If these interactions are atypical or inadequately compensated when impaired, motor impairments can result. Thus it is recommended that every physical therapy examination and evaluation include multisystem screening of the five impairment categories (Box 39-1) in order to determine the impact of each organ system on total motor performance. The following Soda Can Model of respiratory and

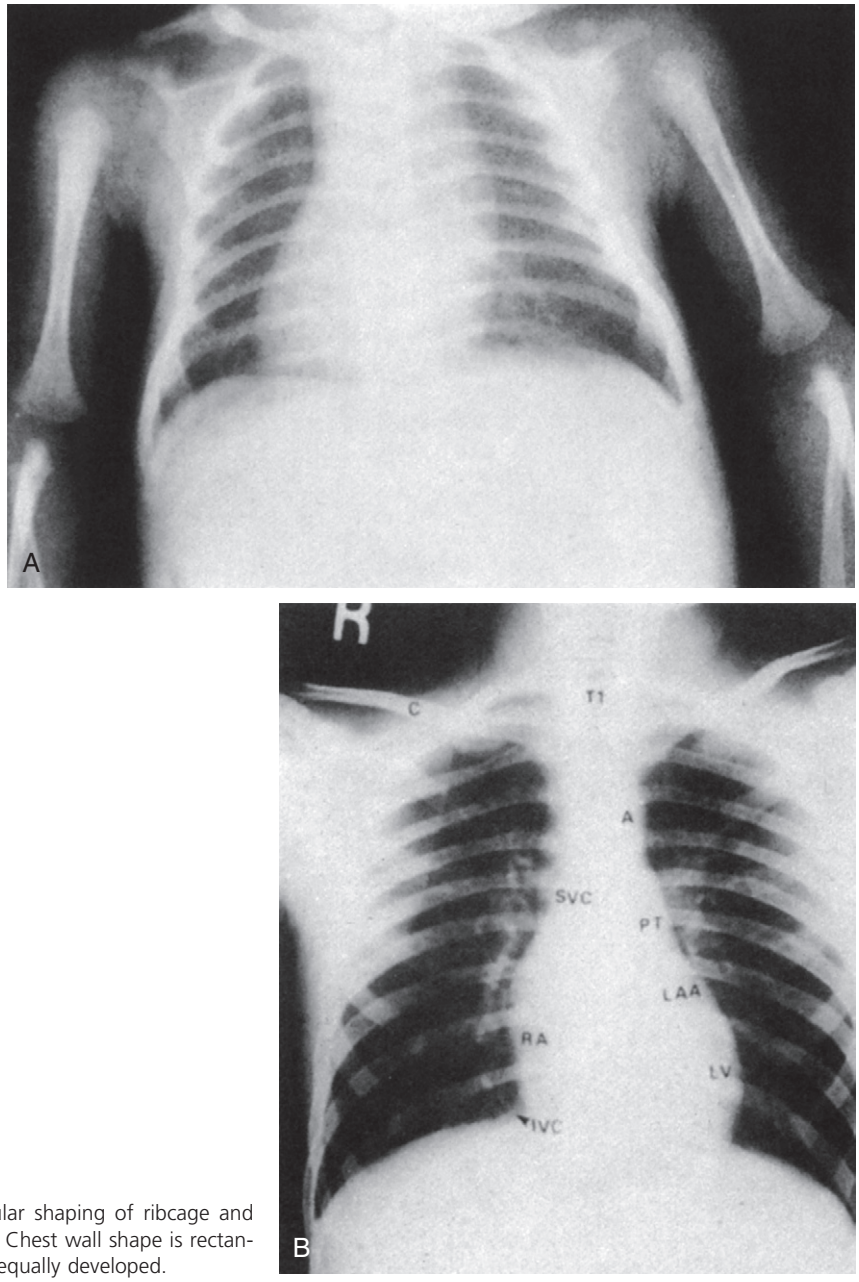


Fig. 39-7 **A,** Chest x-ray of a newborn. Note triangular shaping of ribcage and narrow intercostal spacing. **B,** Typical adult chest x-ray. Chest wall shape is rectangular, ribs angled downward, upper and lower thorax equally developed.

postural control was developed to facilitate the clinician's understanding of the multisystem interactions between the mechanics of breathing and the simultaneous needs of postural control

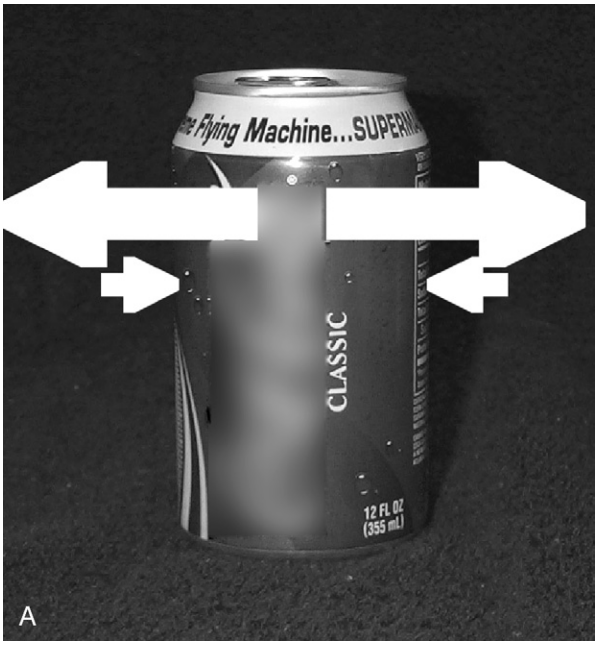
Soda Can Model of Respiratory and Postural Control

The muscles of respiration are muscles of postural support and vice versa.[14] Each muscle that originates from or inserts onto the trunk is both a respiratory muscle and a postural muscle. This duality of function means that respiratory and postural control should not be evaluated separately. External and internal forces that affect the function of the respiratory muscles also affect postural responses. The Soda Can Model illustrates this dual function.

Structurally Weak, Yet Functionally Strong

The shell of a soda or soft drink can is made of thin aluminum that is easily compressed when the can is open and empty. This same can, however, unopened and full, is almost impossible to compress or deform without puncturing the exterior shell. The strength of the can is derived from the positive pressure it exerts against atmospheric pressure and gravity through its closed (unopened) system (Figure 39-8, *A*). As soon as the closed system is compromised by either opening or puncturing the can, it loses its functional strength. It is no longer capable of counteracting the positive pressure forces acting on it. Once the can is opened, it is possible to compress it completely (Figure 39-8, *B*).

The structural integrity of the trunk of the body is similar to that of the soda can described in the Soda Can Model. The



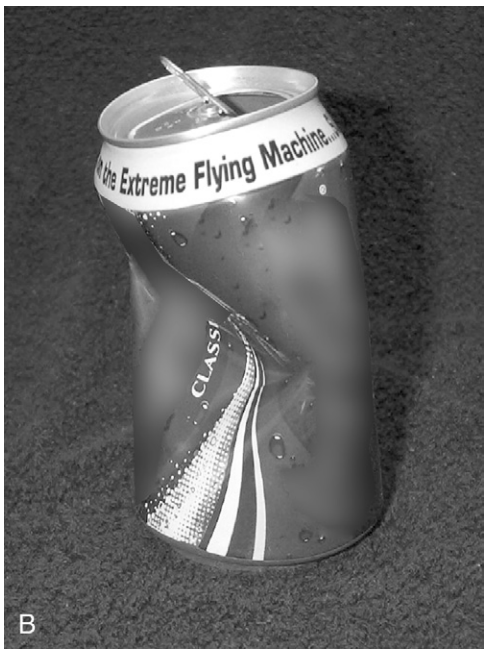


Fig. 39-8 Soda Can Model of respiratory and postural control. **A,** A soda can derives its functional strength because the internal pressure of the carbonated drink is higher than the atmospheric pressure acting on it, not because of its thin aluminum shell. **B,** Without the internal pressure support, the aluminum can is easily deformed and compressed.

skeletal support of the trunk is not inherently strong. The spine and ribcage alone cannot maintain their alignment against gravity without muscular support that enables them to generate pressure that is capable of countering gravitational pull. This is commonly observed in patients in intensive care. Weakened from prolonged illnesses and medical procedures, patients in the intensive care unit (ICU) typically slump into a forward, flexed posture when they sit up initially. This is associated with less ability to generate pressure through muscle activation to support alignment of the pelvis, spine, and

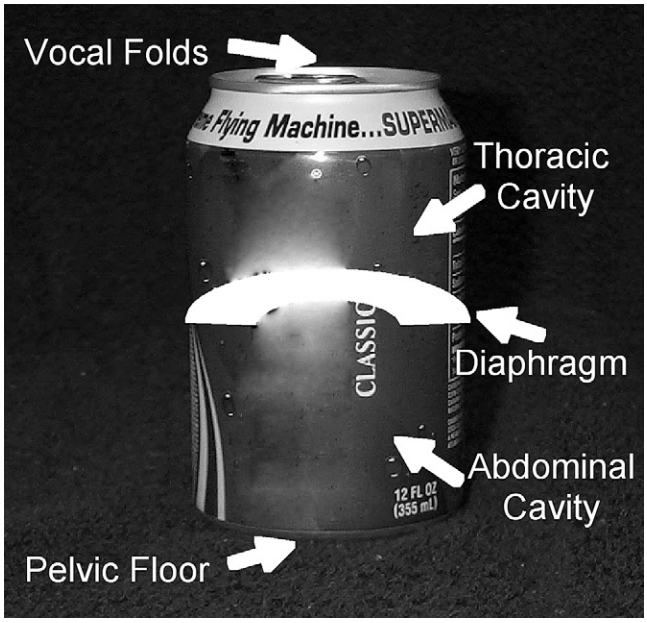


Fig. 39-9 A soda can as a three-dimensional model for trunk muscle support for breathing and postural control. Note that the control of pressure begins at the level of the vocal folds and extends down to the pelvic floor. A breach in pressure anywhere along the cylinder impairs the total function of the can (or, in the human analogy, the function of the patient's trunk).

ribcage in an upright position. In pediatric patients, the effects can be particularly alarming. Melissa provides such an example. She incurred a C5 spinal cord lesion from a vaginal birth injury and experienced marked collapse of the pelvis, ribcage, and spine when sitting upright. Melissa was incapable of making an effective inspiratory effort in this position, which explained her intolerance to upright activities. Figuratively, her "soda can" was compressed, and correspondingly, her breathing mechanics were severely compromised (Figure 39-8, *C*).

Positive Pressure Support Instead of More Skeletal Support

The aluminum can is a chamber. Once the chamber is filled with carbonated fluid and sealed, carbonated gases are released, leading to positive pressure pushing outward, which lends dynamic support to the metal. Likewise, the trunk of the body is composed of thoracic and abdominal chambers that are dynamically supported by muscle activity that generates the positive pressure in both chambers needed to support both respiration and posture.

The thoracic and abdominal chambers are separated by the diaphragm (Figure 39-9). The chambers are "sealed" at the top by the vocal folds, at the bottom by the pelvic floor, and circumferentially by the trunk muscles. Muscle support allows these chambers to match or exceed the positive pressure exerted on them by external forces to support the "flimsy" skeletal shell. The primary muscles involved in this support are the (1) intercostal muscles, which generate and maintain transthoracic pressure[15]; (2) the abdominal muscles, especially the transverse abdominus, which generate and maintain

transabdominal pressure[16,17]; (3) the diaphragm, which regulates and uses the pressure in both chambers[18,19]; (4) the back muscles, which stabilize the spine to optimize its alignment and articulation with the ribcage[20]; (5) the pelvic floor muscles, which work synchronously with the diaphragm to support breathing and urinary control[21,22]; and (6) the vocal folds, which regulate intrathoracic pressure to stabilize the diaphragm and upper extremities.[23] These muscles work synergistically to adjust the pressure in both chambers so that the demands of ventilation and posture are met simultaneously.[24]

The following synopsis of the biomechanics of breathing describes the interactions among the diaphragm, intercostals muscles, and abdominal muscles within the construct of a positive pressure chamber.[24-27] The diaphragm is the primary muscle of respiration, but its function as a pressure regulating muscle may be less well recognized. The diaphragm separates the thoracic and abdominal cavities, thus creating and using the difference in pressure between the two chambers to support the simultaneous needs of respiration and trunk stabilization. The interactions among the diaphragm, intercostal muscles, and abdominal muscles, along with support from other trunk muscles, work synergistically to generate, regulate, and maintain thoracic and abdominal pressures necessary for the concurrent needs of breathing and motor control of the trunk.[28] In summary, the diaphragm depends on the intercostal and abdominal muscles for effective and efficient breathing, and likewise, the trunk depends on the diaphragm for muscular support and pressure support during activities, particularly those with high postural demands.[20,28-30]

When the diaphragm contracts to effect inhalation, its central tendon descends inferiorly, creating negative pressure in the thoracic cavity. This draws air into the lungs due to the pressure difference with atmospheric pressure. Simultaneously, the intercostal muscles are activated to counter the negative pressure that draws them inward.[7,31-34] Inadequate intercostal muscle support tends to collapse the chest wall, which in the long-term can cause musculoskeletal deformity (e.g., pectus excavatum) and secondary loss of chest wall compliance (see Figure 39-2, *B*).[6,7,35,36] With descent of the diaphragm, positive pressure is created within the abdominal cavity and augmented by counterpressure exerted by the abdominal muscles, particularly the deepest muscle, the transverse abdominus.[37] This pressure equals the negative pressure created in the thorax, based on Newton's Law—that is, for every action, there is an equal and opposite reaction.[38] Further, positive abdominal pressure provides a fulcrum for the diaphragm to stabilize its central tendon. This central stability mechanically supports the contractions of the lateral (peripheral) fibers up and over the abdominal viscera (lateral and superior chest wall expansion).[24] That is, the coupling among the intercostals, abdominals, and diaphragm is greater than the sum of their parts for maximal respiratory function.[26,39]

The abdominal cavity has relatively higher pressure at rest than the thoracic cavity, as reflected by the position of the diaphragm within the trunk. Its dome is convex superiorly because the higher pressure from the abdominal cavity pushes it upward. In lung disease, the relationship between the abdominal and thoracic pressures may reverse and compromise the mechanics of breathing. For example, patients who have obstructive lung disease such as emphysema, trap air distally in the diseased lung segments.[40] Air trapping and other manifestations of the condition cause the thoracic cavity to become the higher-pressure chamber at rest, pushing the diaphragm inferiorly and flattening its dome. The diaphragm's mechanical support becomes compromised to the extent that it no longer functions well as an inspiratory muscle. To compensate, patients with end-stage emphysema tend to lean forward on extended arms, flex their trunks, and activate their abdominal muscles to increase abdominal pressure as a means of restoring the pressure relationship with the thoracic chamber. If successful, these patients are able to displace the dome of the diaphragm upward to enable it to function more effectively as an inspiratory muscle, thereby relieving dyspnea.[41]

Top and Bottom of the "Soda Can": The Vocal Folds and Pelvic Floor

VOCAL FOLDS AND VOCAL APPARATUS

Positive thoracic pressure is needed for both postural support of the upper trunk and expiratory maneuvers such as talking, coughing, and bowel and bladder evacuation.[42-44] The vocal apparatus, including the vocal folds, provides the superior valve for pressure regulation of the thoracic chamber. If the vocal folds are compromised because of an impairment of the upper airway or because they are bypassed with a tracheostomy or endotracheal tube, the patient is incapable of generating and sustaining positive thoracic pressure support. After the patient has inhaled and achieved higher pressure inside than outside the lungs, the air is simply expired. There is no valve at the top to hold the pressure within the chest. Activities of the trunk that require positive thoracic pressure will be compromised. Without functioning vocal folds to regulate the controlled release of thoracic pressure during exhalation, the patient has no means of slowly, or eccentrically, releasing the air for speaking or performing eccentric trunk or extremity activities. The therapist may observe impairments such as dysfunctional speech and eccentric motor activity. The same is true for concentric contractions. Without the vocal folds being able to serve as the pressure valve, the patient is unable to generate intrathoracic pressure to elicit an effective cough.[45] Similarly, if the patient is unable to close the glottis and direct thoracic positive pressure toward the pelvic floor, bowel and bladder evacuation may be compromised.[46-49] Patients with tracheostomies often experience constipation. Bowel motility usually improves with decannulation when the vocal folds are restored as an active component of thoracic pressure regulation. The patient with compromised vocal folds can briefly generate positive expiratory pressure for activities such as coughing and yelling by concentrically contracting the trunk flexors, primarily the abdominal muscles, pelvic floor muscles, pectoralis muscles, latissimus dorsi muscles, or some combination, at peak inspiratory lung volume. This positive thoracic expiratory pressure, however, cannot be sustained because the expiratory pathway (e.g., tracheostomy tube or paralyzed vocal folds) is wider than the opening of the vocal folds, resulting in a larger volume of air to be expelled per second. Unlike patients with obstructive lung disease who have an abnormally prolonged expiration, patients with impaired pressure regulation at the top of the chamber have no mechanism to prolong exhalation for either eccentric or concentric motor tasks.

In addition to regulating airflow from the lungs, the vocal folds have a role in generating increased thoracic pressure needed for stabilization associated with balance or activities such as lifting, pushing, and upper extremity weight-bearing activity.[23,50-52] This response is called the glottal effort closure reflex.[43] The vocal folds adduct and prevent air leakage while the chest wall, back, abdominal, and pelvic floor muscles contract to increase abdominal and thoracic pressures. Increased trunk pressure stabilizes the shoulder complex to enhance force production of the muscles of the upper extremities. For example, a tennis player with a strong serve often takes advantage of the glottal effort closure reflex. The server throws the ball up while taking a deep breath, then he or she closes the glottis at the peak of inspiration to trap the inspired air and activate the chest wall and abdominal muscles to increase thoracic pressure. When the tennis racket contacts the ball, the server explosively expels the air (usually with a grunt) to maximize the force production for the serve. This concept is used in every day life to perform tasks such as pushing open a heavy door, lifting a heavy box, or leaning on a table with one arm and reaching across to lift an object with the other arm. This mechanism is also used by infants to bear weight on their arms during activities such as crawling. These types of activities require full or partial glottal closure to increase the functional strength of the arms. This concept is consistent with that of the Soda Can Model, that is, providing a means of regulating pressure to augment functional strength and control.

The importance of the vocal folds as the superior (i.e., uppermost) pressure regulator of the trunk may be observed in a child with a tracheostomy necessitated because of an airway impairment or a paralyzed vocal fold, or in a child with poor vocal control due to other reasons. The physical therapist may observe that the infant crawls with elbow flexion rather than on extended arms, even though there is no muscle weakness in the arms. It is possible that the inability of the vocal folds to maintain adequate positive pressure within the thoracic cavity during weight bearing (glottal effort closure reflex) causes the elbows to flex (rather than weak triceps). In this case, strengthening the vocal folds, or adding a Passy Muir® valve (speaking valve) to a tracheostomy tube may improve the child's potential to generate the positive thoracic pressure needed for energetically demanding postural activities. In other words, restoring the trunk's pressure support system (analogous to the soda can) may lead to greater functional gain than focusing on exercises for the upper extremities.

Other types of vocal fold interactions can influence speech, breathing, and postural control through their effects on this pressurized system. For example, the function of the vocal folds may be improved as a speech valve if the abdominal pressure is improved with an abdominal binder in patients with spinal cord injury.[53,54] For children with upper airway obstruction such as laryngeal malacia, excessive inspiratory flow rates, which create excessive negative pressure in the upper airway, may decrease vocalization or elicit exercise-induced asthma.[55]

PELVIC FLOOR

The pelvic floor muscles provide support at the inferior end of the cylinder, that is, at the base of the abdominal cavity. Dysfunction of these muscles can impair the potential of the abdominal cavity to generate positive pressure.[23] For example, when abdominal pressure is intended to be directed toward the vocal folds for coughing, sneezing, yelling, and laughing, insufficient pelvic floor muscle strength or motor control may reduce positive pressure through the pelvic opening. This is often expressed as urinary stress incontinence, rendering the intended respiratory or postural maneuver less effective.[56,57] Numerous conditions compromise the integrity of the pelvic floor, but most common is the overstretching of pelvic floor muscles during childbirth leading to pelvic floor muscle weakness and inadvertent incontinence, especially during activities such as sneezing, coughing, and running. Women with this condition may cross their legs or perform other pressure-supporting compensatory behaviors to reduce urinary incontinence until their pelvic floor muscles heal. In other conditions, such as cystic fibrosis, women have a high incidence of urinary stress incontinence secondary to repetitive stress on the pelvic floor from the positive pressure associated with chronic coughing.[58,59] Incontinence is not restricted to patients with primary pulmonary disease. Women with low back pain and impaired postural responses also have been reported to have a higher incidence of incontinence.[56]

INTERNAL ORGANS

The organs of the thoracic and abdominal cavities generate or use pressure changes in the thorax and abdomen to augment their functions. The neuromuscular system, for example, creates pressure changes in the thorax and abdomen. The lungs and esophagus use this pressure change to effect efficient breathing and augment upper gastrointestinal motility. The cardiovascular system contributes to small changes in thoracic pressure. Using these changes and the changes from the respiratory mechanics, the heart and vasculature can optimize circulation, blood pressure, and tissue perfusion. The abdomen also uses pressure changes to optimize internal organ function. Rhythmic abdominal pressure is transmitted through the intestines to stabilize the lumbar spine, augment lower gastrointestinal motility, and optimize movement of body fluids including lymphatic drainage (Figure 39-10).[60]

Without pressure support, which includes the rhythmic change in the thorax from negative to positive pressure and the rhythmic change in the abdomen from neutral to positive pressure (making the abdomen the relatively higher pressure system), the function of the internal organs may be compromised. Dysfunction may be expressed as a decrement in blood pressure (hypotension), inefficient breathing, gastroesophageal reflux with or without abnormal posturing such as in Sandifer's syndrome, inadequate bladder emptying (increasing risk for urinary tract infections), and constipation.[61-64] Although these dysfunctions may not result solely from reduced pressure support, it is a major contributor.

Soda Can Model Summary

The Soda Can Model of respiratory and postural control provides a three-dimensional, dynamic illustration of how the trunk meets its concurrent needs for breathing, postural control, and function of the internal organs. When the patient has reduced ability to generate, regulate, and maintain pressure within the thoracic and abdominal chambers, the mechanics of breathing and other body functions may be

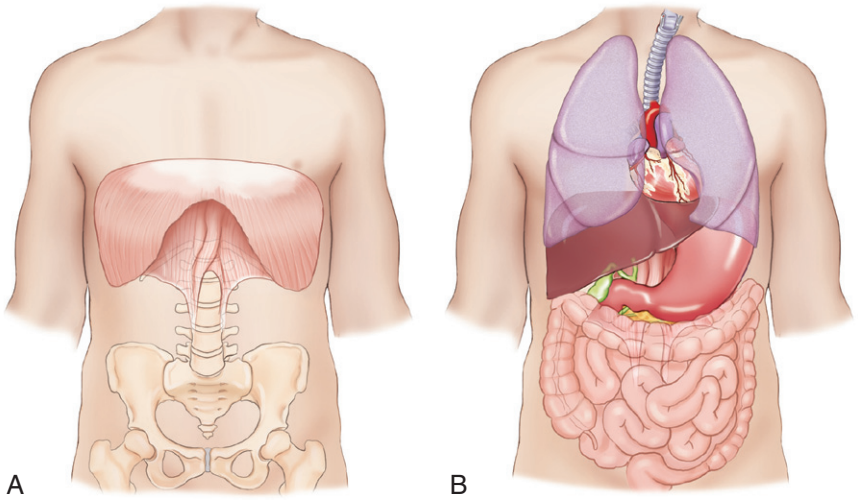


Fig. 39-10 A, Note the position of the diaphragm, which serves as the internal pressure regulator between the thoracic and abdominal cavities. The vocal folds and pelvic floor serve as the external pressure valves. **B,** Note the number and alignment of the internal organs within the thorax and abdomen that are affected by the changes in the diaphragm's position during respiration.

impaired. Inadequate pressure support may begin with an impairment of the mechanics of breathing, such as in a neuromuscular or musculoskeletal disorder. Alternatively, the problem may originate in conjunction with another impairment—for instance, an impairment of the cardiovascular, pulmonary, integumentary, or internal organ system—that nonetheless leads to impaired breathing mechanics. Breathing mechanics are best assessed from a multisystem perspective.

Compensatory Breathing Patterns Associated with Insufficient Muscular Support

As illustrated in the Soda Can Model, the trunk muscles provide the pressure changes necessary for breathing. What happens, however, if the muscles are weak, paralyzed, fatigued, or otherwise nonsupportive? What types of compensatory breathing patterns can be used? Six compensatory breathing patterns are described below and summarized in Table 39-2.

Paradoxical Breathing

Paradoxical breathing refers to opposite movements of the chest wall during normal breathing (occasionally termed belly breathing, see-saw breathing, or reverse breathing). The most common type of paradoxical breathing is caused by strong contraction of the diaphragm in the absence of adequate muscular support from the intercostal muscles and abdominal muscles. The diaphragm contracts, the abdomen rises excessively because weak or paralyzed abdominal muscles do not increase positive abdominal pressure, which limits the descent of the diaphragm. The upper chest wall collapses inward because of inadequate stabilization from the intercostal muscles (see Figure 39-2, *A*). Although not efficient, paradoxical breathing can be sufficient for breathing without mechanical ventilator support for patients with neuromuscular weakness.[7,11]

Another type of paradoxical breathing is observed when the diaphragm is weak or paralyzed and the upper accessory

Table 39-2 Compensatory Breathing Patterns Associated with Insufficient Muscular Support

Paradoxical breathing	a. Functioning diaphragm with paralyzed or weak intercostals and abdominal muscles b. Paralyzed or weak diaphragm with functional accessory muscles; may or may not have functioning abdominal muscles
Diaphragm and upper accessory breathing	a. Paralyzed or weak intercostals
Upper accessory muscles breathing	a. Paralyzed or weak diaphragm and intercostals; abdominal muscles may or may not be functional
Asymmetrical breathing	a. Paralyzed or weak thoracic muscles on one side b. Often associated with hemiparesis or scoliosis
Lateral or "gravity-eliminated" breathing	a. Generalized weakness, no paralysis b. Breathing takes place in the plane with the least resistance to gravity c. Often associated with weakness due to prolonged illness
Shallow breathing	a. Small tidal volumes b. Often associated with high neuromuscular tone or painful conditions

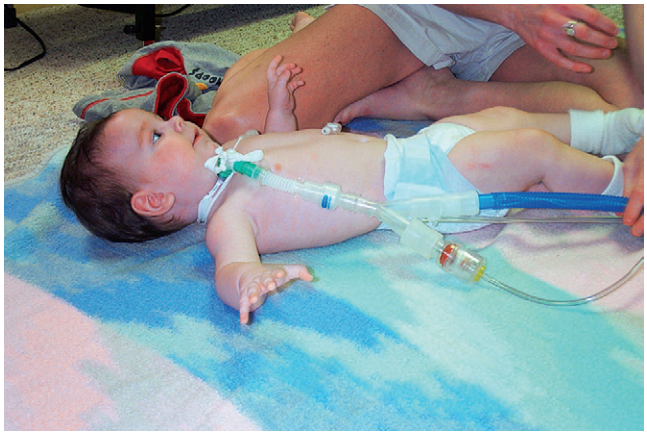


Fig. 39-11 Nicholas, 1 year of age. Nicholas was born with both hemidiaphragms paralyzed and requires full-time mechanical ventilation. When he is off the ventilator for brief periods of time to assess his independent breathing pattern, he demonstrates the second type of paradoxical breathing: a rising upper thorax and falling abdomen during inhalation.

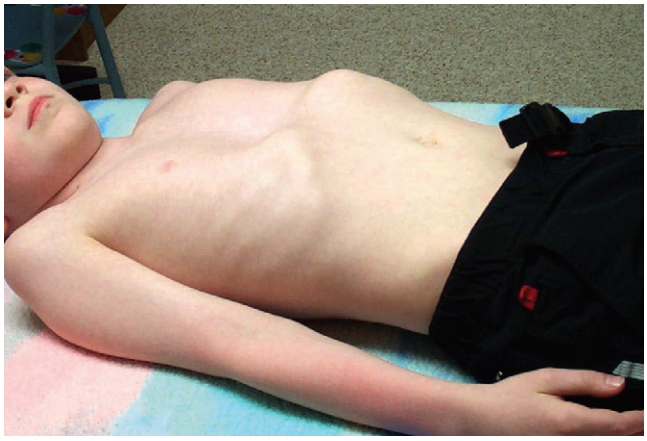


Fig. 39-12 Justin, 9 years of age. Justin has a congenital pectus excavatum. No neurological impairment. His breathing pattern is primarily diaphragm and upper accessory muscles. Note the persistent elevation of the ribcage and the inward collapse of the lower sternum (pectus excavatum). Justin's sternum moved paradoxically with every inspiratory effort, especially during high respiratory and postural demand.

muscles remain intact. The abdominal muscles may or may not be functional. The inspiratory action is opposite to the motion that was described for the most common type of paradoxical breathing (Figure 39-11). The abdomen is drawn inward by the negative pressure in the thorax created by the upper accessory muscle during inhalation. The chest wall rises and the abdomen falls. Generally, this type of paradoxical breathing requires at least partial mechanical ventilatory support because the accessory muscles cannot adequately meet the needs of long-term independent ventilation. In addition, they are more likely to fatigue and lead to respiratory distress. The loss of the diaphragm as the primary respiratory muscle results in greater inspiratory volume deficits than the loss of just the accessory-muscles support observed in the prior paradoxical breathing pattern. Loss of the diaphragm as the primary pressure regulator for the trunk also contributes to deficits in postural control.

Diaphragm and Upper Accessory Muscles Only (Paralyzed or Nonfunctional Intercostal Muscles)

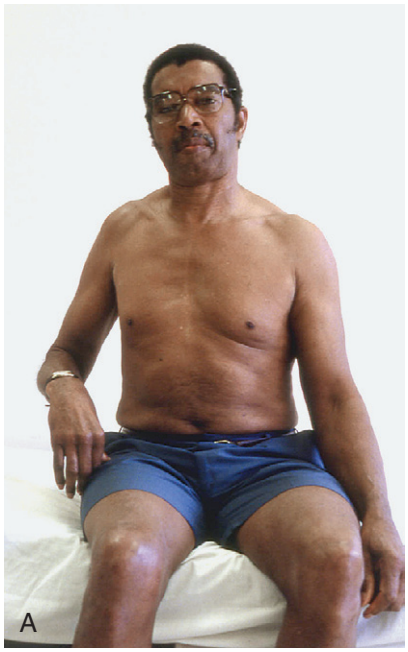
Another type of compensatory breathing pattern can be observed when the intercostal and abdominal muscles are paralyzed or weak but the diaphragm and upper accessory muscles continue to function (i.e., patients with tetraplegia, high paraplegia, some congenital pectus excavatum deformities, upper airway obstruction, and asthma). These patients counterbalance the strength of the diaphragmatic inferior pull by using their sternocleidomastoid muscles and possibly their scalene, trapezius, and pectoralis muscles. Allowing for superior and possibly some anterior and lateral expansion of the chest wall, this compensatory breathing pattern minimizes the collapse of the upper chest wall that is observed in paradoxical breathing. This must be cognitively coordinated with inspiration. This pattern can be an effective breathing pattern for patients with neuromuscular weakness but may be less efficient for patients with asthma. On assessment, these patients can present with shortened neck muscles. Intercostal retractions (the collapsing of the intercostal spaces on inspiration) may be observed, especially at the level of the xiphoid. Paralyzed or weak intercostal muscles will be sucked in toward the lungs during negative pressure generated within the thoracic cavity, which can lead to intercostal retractions and can develop into a pectus excavatum in the long-term (Figure 39-12).[6,65]

Upper Accessory Muscles Only

If the patient cannot recruit the diaphragm, intercostal, and abdominal muscles, then independent breathing can be achieved only by using the upper accessory muscles in the superior plane and limited anterior expansion. These patients often require mechanical ventilation to augment their breathing independently because the lung volumes they are able to generate are insufficient to support the oxygen needs of the body.

Asymmetrical Breathing

Asymmetrical movement of the chest wall in patients with stroke, scoliosis, or other conditions is often associated with an asymmetric breathing pattern. This pattern is generally sufficient for breathing without mechanical ventilation because the strong side compensates for the weak side.[66] This compensation, however, may lead to asymmetric alignment of the trunk that adversely affects postural control in upright body positions. In addition, the adverse effects on posture can lead to adverse musculoskeletal changes over time, especially in the pediatric patient whose musculoskeletal system is still maturing.[67] Prevention of these secondary changes is a clinical priority[68] (Figure 39-13).



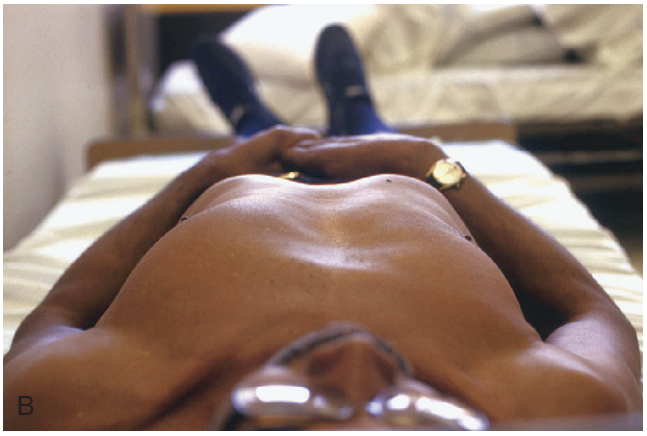


Fig. 39-13 Charles. Right hemiparesis from a stroke. **A,** Note asymmetry of the trunk in sitting during breathing and postural control. **B,** Note the weakness in the right upper thorax. Charles' right upper thorax moved less during inhalation than the left, which accentuated his asymmetrical trunk alignment and may have been a contributing factor to his impaired posture and upper extremity function in stance and during gait.

Lateral or Gravity-Eliminated Breathing

Patients with generalized weakness such as that associated with benign hypotonia, prolonged illness, or incomplete spinal cord injury, may breathe wherever gravity provides the least resistance. For example, in a supine position, patients with weakened chest wall muscles cannot effectively oppose the force of gravity in the anterior plane; thus they alter their breathing patterns to expand their chest walls primarily in the lateral plane in which gravity is eliminated. In sitting, these patients tend to breathe inferiorly where gravity assists the movement. Likewise, in a side-lying position, they tend to breathe in the anterior plane. Because their muscles are weak rather than paralyzed, these patients have a positive prognosis with respect to breathing retraining methods.

Shallow Breathing

Shallow breathing can result from injuries to the central nervous system. Such impairments include high tone associated with Parkinson syndrome, head injuries, and cerebral palsy. Shallow breathing occurs secondary to high neuromuscular tone (e.g., spasticity, rigidity, and tremors), which severely limits chest wall expansion in any plane; cerebellar discoordination; and/or improper neuromotor sequencing because of lesions in the brain, most commonly associated with medullary lesions. Shallow breathing may also occur secondary to pain, including low back pain. In such cases, breathing patterns are altered less from muscle weakness and more from the patient limiting his or her thoracic movement, thereby changing thoracic pressure. The breathing pattern is usually symmetrical, shallow, sometimes asynchronous, and frequently tachypneic (respiratory rates over 25 breaths/min for adults). Initiation and follow-through of a volitional maximal inspiration can be difficult or impossible for patients. This will markedly curtail the ability to produce an effective cough, maintain bronchial hygiene, or yell.[29]

Application of the Soda Can Model to a Clinical Example

Inherent in the Soda Can Model of respiratory and postural control is the concept that impaired pressure regulation of the trunk may result from an impairment in any organ system that generates or uses this pressure. Organ systems therefore need to be screened for their role in the motor dysfunction of breathing, postural control or both. Five impairment categories were identified at the beginning of this chapter (see Box 39-1) as well as six functional activities that require the effective coordination of the mechanics of breathing and the postural demands of motor tasks (see Box 39-2). A clinical case illustrating these points follows.

Multisystem Evaluation, Examination, and Intervention

Case History

Katie is a 9-year-old girl (Figure 39-14, *A*) diagnosed with congenital idiopathic scoliosis (infantile scoliosis) that required surgical stabilization of two upper thoracic vertebrae when she was 3 years old. After surgery, several ribs became fused on the concave side of the scoliosis and contributed to progressive kyphoscoliosis as Katie matured. Spinal fusion from T1 to S1 was planned when she was 9½ years old, when the scoliosis reached 98° despite conservative bracing from 3 years of age and close monitoring by the orthopedic surgeon.

The presurgical work-up revealed that Katie's lungs were severely restricted by her musculoskeletal impairment; the pulmonologist was unsure she would survive surgery. Figuratively speaking, Katie's soda can was crushed, resulting in dysfunction of multiple organ systems, even though the original impairment was in a single system, the musculoskeletal system. Katie was referred to physical therapy with the goal of improving her restrictive lung pathology so that she could become a viable surgical candidate. Katie had not been referred to physical therapy previously.

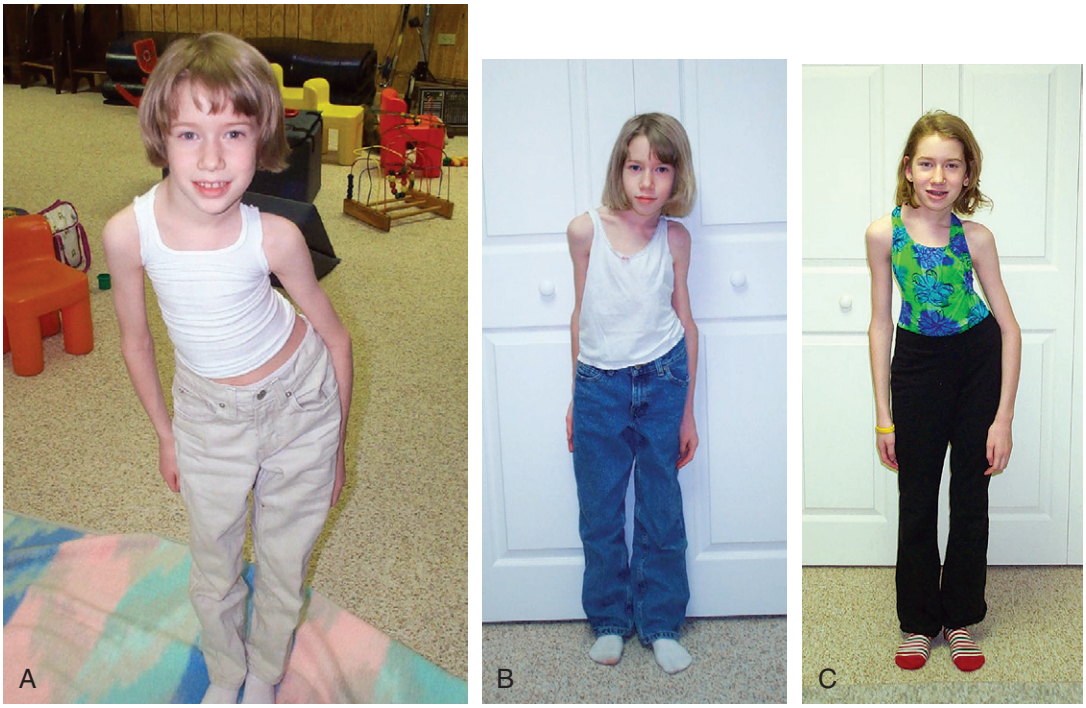


Fig. 39-14 A, Katie, 9 years of age; diagnosis of infantile scoliosis. Presurgical workup showed her FVC at 33% of predicted value. **B,** Katie, age 10 years old. 1 year later. Her surgeon believed that the improvements in lung volumes and a slight reduction in the scoliosis would allow him to postpone the surgery, giving Katie more time to grow before the surgery blunted her adult height. Katie's loose shirt partially occludes the severity of the spinal deformity. **C,** Katie, age 13 years old. 6 months after back surgery. Scoliosis was reduced as much as possible given her fused ribs (from surgery as a toddler) and other joint limitations.

IMPAIRMENT CATEGORIES

Based on a multisystem examination and evaluation based on the Soda Can Model, Katie's pathology was no longer regarded as motor dysfunction resulting from one system. The progression of her impairments, starting with the original insult to the musculoskeletal system, is described in Table 39-3.

1. Katie's pathology originated in the musculoskeletal system, specifically her spine. Her skeletal support, the "aluminum can," had collapsed over her growing years. Katie's muscle support matured around those deformities and did not develop optimal length tension relationships. Her weakness primarily involved the muscles of the trunk and proximal joints. Her distal extremity muscles showed less weakness. In particular, her intercostal muscles were so weak from disuse that the negative pressure of inhalation caused her chest wall to be drawn inward (paradoxical breathing). She was unable to generate sufficient muscle force to counteract the internal negative pressure associated with normal inspiratory lung volumes. Although the paradoxical movement had not led to a pectus excavatum, this possibility remained. Her hips and shoulders matured around her malaligned spine, which resulted in additional joint dysfunction. Katie's mother reported that her daughter had never been a physically active child, which was expected given her multiple joint limitations.
2. Katie's musculoskeletal weakness resulted in a secondary neuromuscular problem. Her muscle recruitment and balance strategies developed to compensate for atypical musculoskeletal alignment that neither supported the symmetrical development of her body nor effectively supported the concurrent demands of thoracic pressure support for the control of respiration and posture. As a result, Katie's breathing pattern was atypical (paradoxical) and this likely contributed to reduced lung volumes.
3. Reduced lung volumes and limited physical activity could explain Katie's marked endurance and mechanical impairments related to the cardiovascular and pulmonary systems. Her breathing mechanics and potential lung space were compressed to the extent that she developed severe restrictive lung pathology. No heart or vascular problems were reported by her physician based on her initial evaluation. Right heart failure, however, which can develop secondary to chronic pulmonary dysfunction, was a risk for Katie as she matured.
4. The shape of the scoliosis severely compressed Katie's stomach, causing internal organ impairment and, in turn, undernutrition and dehydration. Katie ate less than 200 calories at each meal due to premature satiety. Fluids made her feel full faster, which further compromised her hydration and capacity to consume sufficient calories. Fortunately, she did not develop gastroesophageal reflux from the abnormal thoracic and abdominal pressures and musculoskeletal malalignment.
5. Katie's integumentary system appeared to have adapted to her deformities. Her surgical scars had healed and had not adhered to underlying structures. Despite severe spinal deformity, the connective tissue around Katie's trunk and extremities was easily moved. This permitted maximum mobility of the underlying skeletal structures. Adhered integument and connective tissue were possibilities.

Table 39-3 Identifying Katie's Motor Impairments from a Multisystem Model and Planning a Targeted Intervention Strategy

Impairment Categories	Musculoskeletal	Neuromuscular	Cardiovascular/ Pulmonary	Integumentary	Internal Organs
Identify primary pathology	Scoliosis				
Identify the progression of impairments	Musculoskeletal→	Neuromuscular→	Cardiovascular/ Pulmonary→	Internal organs→	(Integumentary)
List current impairment problems	**Musculoskeletal**: Abnormal joint alignment, proximal worse than distal; abnormal length tension relationship of all muscles affected by joint malalignment resulting in weakness proximal > distal **Neuromuscular**: Trunk muscle weakness and malalignment resulting in the development of inadequate postural control strategies and a constant conflict between breathing and postural needs **Cardiovascular/pulmonary**: severe restrictive lung condition resulting in significant endurance impairments; impaired breathing mechanics, including paradoxical breathing (weak intercostal muscles); RR 32 breaths/min (tachypneic); forced exhalations even at rest; weak cough; chronic nocturnal hypoventilation; inadequate respiratory reserves for inhalation or exhalation demands; 3-5 syllables/breath (normal 8-10); sustained phonation 2-3 sec (normal 10 seconds); no cardiac symptoms (yet) **Integumentary**: No connective tissue limitations around scars from previous surgeries or around her shoulders or pelvis **Internal organs**: Malnutrition; dehydration; no reflux;				
Functional limitations and impact on participation	Functional limitations were noted in all activities that required greater oxygen or caloric fuel than Katie's restricted body could provide or that required effective coordination of breathing with movement. This resulted in limitations from the most basic motor activity of breathing to limitations in coughing, sleeping, talking, eating, and moving, thus causing severe limitations in Katie's ability to participate in normal childhood activities such as running, walking, biking, etc.				
Prioritize the current problems by categories	Internal organs→	Musculoskeletal→	Neuromuscular→	Cardiovascular/ Pulmonary→	(Integumentary)
Diagnosis	Nine-year-old girl with congenital idiopathic progressive kyphoscoliosis with severe secondary restrictions to her breathing mechanics and lung growth, nutritional health, strength and alignment of the entire musculoskeletal frame, resulting in pain, endurance impairments, significant health risks, and overall limitations in the child's physical capabilities and participation.				
Prognosis	Marked compromises of the musculoskeletal and neuromuscular support for breathing and movement, combined with Katie's poor nutritional status, limit the pulmonary status she needs immediately for surgical clearance. I believe that Katie can improve the alignment, mobility, strength, and control of her ribcage and respiratory mechanics necessary to meet the pulmonary demands of surgery if given enough time to achieve a true change in the muscle function (minimum of 4-6 weeks of training). After surgery, Katie will need an aggressive physical therapy program to develop new neuromuscular strategies that effectively utilize her new musculoskeletal alignment to maximize breath support and postural control in order to reduce her long-term cardiopulmonary, nutritional, and musculoskeletal health risks, as well as to increase her potential to participate in normal childhood activities.				
Pre- and postsurgical goals	**Presurgery**: Improve nutritional status, hydration, skeletal alignment of the trunk, and strength and control of the thoracic musculature in order to improve Katie's breathing mechanics and cough effectiveness so that she can survive the scoliotic reduction surgery and the recovery phase. **Postsurgery**: Use Katie's improved breathing mechanics to initiate an effective airway clearance program and to develop neuromuscular strategies to utilize and maintain her new spine alignment in order to reduce the risk for postsurgical pulmonary complications and to maximize breath support and postural control long term in order to reduce her ongoing cardiopulmonary, nutritional, and musculoskeletal health risks and to increase her potential to participate in normal childhood activities.				
Interventions specific to Katie's short-term goal of surgical readiness	**Musculoskeletal**: Rib mobilization to maximize inspiratory lung volumes; other ROM of joints as needed. **Neuromuscular**: Neuromuscular reeducation to increase intercostal activation for inspiratory lung volumes and chest wall stabilization; neuromuscular reeducation to reduce recruitment of abdominal muscles for forced exhalation strategies; incorporation of new breathing pattern into postural demanding tasks starting with low level activities such as walking. **Cardiovascular/pulmonary**: Endurance training—ventilator muscle training, including both resistive inspiratory and expiratory devices to increase respiratory endurance and low level power production; power training—using peak flow meter and incentive spirometers for visual feedback for maximal effort breathing; coughing strategies for improved airway clearance. **Integumentary**: No short-term interventions needed. **Internal organs**: Devised plan for increasing overall hydration and caloric intake through multiple small meals/snacks and constant sipping of water throughout the day, including school hours; school approval was critical to carryover.				

FUNCTIONAL LIMITATIONS

A functional assessment was conducted to cross-reference the evaluation from both perspectives: impairments and functional limitations. The functional findings were consistent with the impairment findings: Katie had marked functional limitations due to impaired breathing mechanics that were impacting her quality of life.

1. Katie's breathing pattern at rest showed excessive diaphragmatic excursion, underuse of the intercostal muscles (especially on the left, concave side of her chest wall), and paradoxical breathing. Her respiratory rate (RR) was 32 breaths per minute with forced exhalations (normal RR is 10 to 20 breaths/minute). With minor increased physical workload, such as walking fast, she responded by breathing faster rather than deeper. Consistently, Katie had limited physical endurance compared with her peers. Her forced vital capacity (FVC) was 33% of predicted for her sex, age, and height, indicating severe restrictive lung pathology.
2. Her cough neuromotor sequence was normal, but the small lung volume impaired her expiratory force. Her peak expiratory flow rate (PEFR) was 59% of predicted. Clinically, less than 60% of predicted PEFR has been associated with an ineffective cough and increased risk of secondary pulmonary complications.
3. Katie's teachers reported that she fell asleep most afternoons in school and often complained of headaches. Given her severe restrictive lung pathology and weak thoracic muscles, nocturnal hypoventilation was suspected. A sleep study 3 years earlier showed no abnormalities. Hypoventilation due to fatigue can contribute to poor lung function during the day and could account, in part, for her limited growth. Her pulmonologist concurred and ordered another sleep study. Chronic hypoventilation was confirmed.
4. According to her mother, Katie had always been a quiet child. The question was whether she was naturally quiet or whether she was conserving energy. Her speech consisted of three to five syllables per breath. Normal speech consists of 8 to 10 syllables per breath.[43] Katie's sustained phonation of a vowel was 2.4 to 3.1 seconds (normal is 10 seconds).[43] Katie yelled on demand, but her mother reported that she rarely did so spontaneously. Her lack of breath support could explain her quiet speech, short answers, and apparent reserved style. It was not possible to establish whether Katie was quiet by nature or had become quiet as a result of a lifetime of poor breath support.
5. Katie's stomach was compromised by kyphoscoliosis, which contributed to her feeling full after consuming fewer than 200 calories. Not only did Katie have poor weight gain as she grew, but as she aged and needed more calories for vertical growth, she lost weight. Furthermore, she failed to achieve even conservative vertical height goals that had been anticipated by her orthopedic surgeon prior to scheduling Katie for a spinal fusion.
6. Katie had marked endurance limitations for age-appropriate physical activities. She fatigued when walking more than 1½ lengths of the school gym or riding her bike more than 1½ blocks. Katie's weak muscles and impaired breathing mechanics, combined with malnutrition, dehydration, and impaired oxygen delivery, meant that she had less physiological reserve capacity for activities beyond those for basic survival. Katie's body was unable to meet the needs of both breathing and high postural demands of childhood activities.[28,30] Katie preferred to engage in low energy cost activities such as playing the violin, reading, and playing quietly.

PRIORITIES OF INTERVENTIONS

Understanding Katie's progression of impairments streamlined the screening process. The status of Katie's pulmonary system precluded her having surgery. Her primary pathology, however, had not originated in the pulmonary system. This presented several questions: How had all five motor impairment categories contributed to her current pulmonary status? How could treatment interventions be prioritized to meet Katie's short-term respiratory and surgical goals? In the short term, the evaluation led to the several interventions that are described below. Katie's long-term health and participation goals were developed after surgery.

1. Katie's poor nutritional status meant she had minimal energy reserve to participate effectively in a conditioning program to strengthen her respiratory muscles in preparation for surgery. Likewise, her dehydrated state could reduce the mobility of pulmonary secretions, thus increasing her postsurgical risk for atelectasis and pneumonia. Thus, addressing Katie's nutritional and hydration needs was the first priority. Katie was instructed to eat at least six meals daily rather than three. She was permitted to use a water bottle in class. In school, she was encouraged to drink at the start of every new subject. Her nutritional intake was managed by her pediatrician.
2. Surgery was the recommended intervention to improve the alignment of Katie's spine and ribcage. In the short term, however, manual mobilization of her ribcage was a priority to gain movement to augment lung volumes.
3. After Katie's ribcage mobility was increased and a body position identified that gave her the best support for chest wall movement, specifically, sitting, a neuromuscular rehabilitation program was initiated to improve her respiratory mechanics. The goals of the program were:
   a. To increase recruitment, strength, and function of the intercostal muscles as inspiratory muscles (to increase lung volume) and as chest wall stabilizers (to minimize paradoxical breathing), while decreasing the use of forced abdominal muscle exhalations, thus reducing the energy cost of breathing (by manipulating thoracic pressure more effectively).
   b. To increase the power generated by both the inspiratory and expiratory muscles needed to increase lung volumes and cough effectiveness. This was achieved with the use of peak flow meters and incentive spirometers that provided Katie with visual feedback of specific targeted performance (large effort, low repetitions).
   c. To increase endurance and overall fitness of the respiratory muscles through use of an aggressive daily ventilatory muscle training program involving both the inspiratory and expiratory muscles (low resistance, high repetitions) (see Chapter 26). Ventilatory resistance muscle training was used instead of a traditional fitness training program such as treadmill walking because Katie's weakness, malalignment, and painful joints likely would have prevented her from exercising

sufficiently to elicit a favorable response and may have contributed to additional joint problems.

d. To improve Katie's ability to meet the conflicting needs of respiration and postural control required for functional endurance and motor performance, low-level activities (e.g., walking) were prescribed initially, with distance being increased over time (with increased endurance). Katie was instructed how to use the new breathing pattern during functional tasks designed to challenge her balance and breathing simultaneously.

4. In anticipation of orthopedic surgery, ensuring effective pulmonary hygiene was the goal. The contributions of her various body systems to the efficiency and effectiveness of her breathing mechanics, lung volumes, cough effectiveness, endurance, and posture were targeted through multiple interventions.
5. Katie's integumentary system did not show any impairment and was not a major contributor to her limited pulmonary status. After surgery, however, dehydration predisposed her to skin breakdown and poor tissue healing. She was monitored for residual problems.

DIAGNOSIS AND PROGNOSIS

Katie's musculoskeletal pathology impaired the structural support of her trunk and respiratory mechanics. Musculoskeletal restrictions contributed to dysfunction in other systems due to their various interactions. She was referred to physical therapy for one reason, to improve breathing mechanics so that she could undergo surgery to correct the initial pathology, the scoliosis. Based on the physical therapy examination, the pulmonologist was informed that Katie's condition showed potential for improvement. A minimum of 4 to 6 weeks was needed to achieve a training effect that would sustain her through the long surgery. Surgery was postponed for 8 weeks to allow Katie the maximum benefit of the physical therapy intervention. With respect to the long-term goals of health and participation in typical childhood activities, improving her breathing mechanics was only one goal. Other goals were to be addressed after surgery.

OUTCOMES

Katie and her mother understood the risks of surgery and were motivated to participate in an aggressive physical therapy program that relied heavily on home participation. Katie and her mother were instructed regarding the necessity of a home exercise program five days a week for 5 to 6 weeks in order to increase muscle strength and endurance. Katie was enthusiastic: exercising every day. Pulmonary function improvements are shown below, along with their influence on her surgical status.

1. Katie's pulmonary function baseline for FVC was 0.45 L (33% of predicted, or 1.36 L), and her PEFR was 1.64 L/s (59% of predicted).
   a. Three weeks later, Katie's FVC improved to 0.57 L (42% of predicted).
   b. Five months later, FVC had increased to and stabilized at 0.63 L (45% of predicted).
   c. Three months after initiating her program, Katie's PEFR improved to 2.31 L/s (81% of predicted), which is within a normal range for effective coughing.
   d. Two years later, after a sleep study confirmed chronic hypoventilation and after successful initiation of noninvasive mechanical ventilatory support at night, that is, bi-level positive airway pressure (BiPAP), Katie's FVC had improved to 0.71 L, but this value was now only 40% of predicted for her sex, age, and height (1.78 L). Pulmonary function progressively increases with age until adulthood, but Katie's lungs did not keep pace with expectations for a typically developing child. A predicted FVC of 60% is often used as the clinical index of adequate lung volume necessary for normal pulmonary maneuvers such as coughing, sighing, and sneezing. With an FVC of 40% of predicted, she was still at long-term risk for secondary respiratory problems due to impaired lung volumes.
2. At 4 months, the orthopedic surgeon recommended postponing surgery because her scoliosis was reduced progressively from 98° to 91°. He believed that her improved pulmonary status had a positive effect on her skeletal frame and that as long as she remained stable, it was worth postponing surgery to give her every chance to grow and continue making respiratory gains before undergoing a spinal fusion (Figure 39-14, *B*).
   a. Katie's surgery was postponed for over 3 years, until she was 12 years old, allowing her to achieve more vertical growth before surgery. The orthopedic surgeon expressed surprise that surgery had not been indicated before Katie reached 10 years of age.
   b. Katie continued to do her exercises three to four days a week over the course of intervention. She had no postoperative respiratory complications. Her scoliosis was markedly reduced (Figure 39-14, *C*). Additional surgeries may eventually be required for her shoulders, hips, and fused ribs.

Katie's ongoing care included interventions such as gastric surgery for placement of a gastrostomy tube that was needed to improve her nutrition, growth hormone administration, BiPAP nocturnal support to reverse chronic hypoventilation and its effects on her physical endurance and growth, and a comprehensive physical therapy program focusing on her growth and postural maturation. This case history focused on the initial physical therapy intervention to illustrate how a multisystem assessment can be used to develop a differential diagnosis regarding her physical and pulmonary limitations. Katie's scoliosis and muscle development made her incapable of generating, maintaining, and regulating adequate pressures in her thoracic and abdominal cavities to support normal respiration, postural control, and internal organ function. The Soda Can Model helped explain why the impairment of her musculoskeletal system had major implications for her health and the function of other systems.

QUALITY OF LIFE

In addition to Katie's medical improvement, her mother reported that the respiratory and multisystem approach to her daughter's physical therapy program "absolutely saved her life." Katie appeared increasingly confident in her abilities, which was noted at the second physical therapy visit, during which she appreciated the positive results of her diligent adherence to the home program. Within 6 months of the initiation of the physical therapy program, Katie's paradoxical

breathing was eliminated, she no longer used forced abdominal exhalations, her chest wall expansion improved, and her sustained phonation improved 50% (from 3.1 seconds to 4.7 seconds); all of which appeared to contribute to her increased physical activity. She began swimming lessons, joined recreational softball, and generally reported that she "likes this new feeling; it's easier to move and breathe." Her mother reported that Katie smiled more often.

CLINICAL RELEVANCE OF THIS CASE REGARDING IMPAIRED RESPIRATORY MECHANICS AND POSTURAL CONTROL

The cardiovascular and pulmonary systems are systems that create and use pressure support within the trunk's cavities to maximize performance; thus they should not be assessed or treated in isolation. Rather, they need to be assessed in conjunction with other organ systems. The body functions as a whole with individual systems interacting and supporting one another. In particular, postural control and mechanical support for breathing are interdependent; yet breathing necessarily takes precedence over postural requirements. Therefore mechanical support for breathing needs to be assessed and treated within the context of the mechanical support for postural control because both activities use the same muscles.

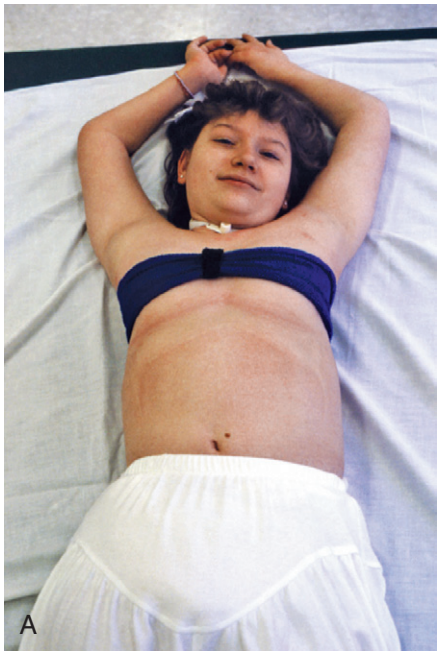
Although Katie's initial pathology originated in the musculoskeletal system, her more important problems, clinically, involved the neuromuscular system (motor planning and strength), the cardiovascular and pulmonary systems (severely impaired respiratory mechanics, inadequate respiratory endurance, and the risk for cardiac impairments), and the internal organs (persistent undernutrition and dehydration). If Katie had been treated based on an impairment of one system, she may not have achieved comparable clinical and functional outcomes that allowed her surgeon to delay her surgery for 3 years and allowed her to achieve other health and functional outcomes.

Application

Pathologies stemming from any motor impairment category may result in impaired breathing mechanics, a conflict in postural control and breathing that interferes with motor performance, or both. For example, a patient with a neuromuscular condition such as a spinal cord injury (SCI), cerebral palsy, stroke, or head injury will have impaired breathing mechanics and impaired postural control due to paralysis, weakness, or impaired motor planning or execution. The physical therapist needs to assess such a patient from a neuromotor perspective, as well as from that system's interaction with the musculoskeletal, cardiovascular, pulmonary, integumentary systems and the internal organs. This helps ensure that the major limitations affecting motor performance and health are identified and prioritized for intervention. Improvements in chest wall and thoracic alignment can be achieved in the long term from a multisystem approach. See Melissa's changes from 3 to 12 years of age after an SCI incurred at birth (compare Figures 39-15 and 39-16 with Figures 39-2, *B,* and 39-8, *C*). Melissa's chest wall and spinal deformities were almost completely reversed after years of interventions from a multiprofessional team approach to her multisystem impairments.[11] Melissa was not assessed or treated by a physical therapist or other rehabilitation professional until she was 3½ years old. Key long-term interventions and outcomes follow.

Fig. 39-15 Melissa, 6 years of age. Note the use of the thoracic-lumbar-sacral orthosis with an abdominal cutout supported by an abdominal binder. This provided support for her developing spine and trunk while still allowing for optimal support for breathing mechanics. Note that the TLSO provided ideal alignment of the proximal extremity joints (shoulders and hips), as well as ideal head alignment for normal functions such as talking and eating.

1. Melissa used an abdominal binder whenever she was upright to provide the abdominal pressure needed for internal organ support, improved breathing mechanics, and lumbar stabilization. This is a lifelong intervention.
2. Melissa also needed a body jacket or thoracic-lumbar-sacral orthosis (TLSO) with an abdominal cutout and abdominal binder. An abdominal binder alone would not provide adequate support for her developing spine and proximal joints. She still developed a scoliosis, but she did not develop a kyphosis or axial rotation of the curve. The orthopedic surgeon stated that this made surgical correction easier, safer, and faster.
3. An aggressive neuromuscular reeducation program was implemented to teach Melissa how to engage her upper accessory muscles, especially her pectoralis muscles, as substitute chest wall stabilizers and how to use them as long-term inspiratory muscles to balance the excessive inward pressure generated by the isolated contractions of the diaphragm. She was also instructed on how to use her breath support (ventilatory strategies) to improve the efficiency of her mobility skills such as in rolling over and reaching.
4. An airway clearance program was developed to minimize the family's reliance on suctioning. Melissa and her family learned multiple manual assistive coughing techniques that effectively expectorated mucus. They reduced her suctioning from 24 to 36 times daily to one to three times



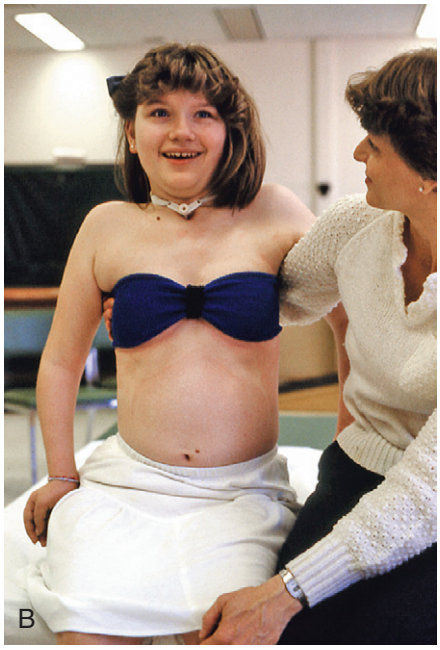


Fig. 39-16 Melissa, 12 years of age, after orthopedic surgery to reduce scoliosis. **A,** Note that the chest wall deformities that were prevalent at 3 years old are almost absent. The only apparent skeletal restriction is the slight reduction in mid-thoracic expansion around ribs 6 and 7, which looks like a high "waistline" just under her bra-strap line in supine position. The intercostal muscles, which were paralyzed, are the only muscles supporting the ribcage at that level. Melissa used her upper accessory muscles, especially her pectoralis muscles, to support breathing and chest wall alignment around ribs 1-5 and her diaphragm around ribs 8-10. **B,** Melissa continues to wear an abdominal binder in upright postures, but it was removed for this picture.

daily. She had multiple bouts of pneumonia in her first 3½ years of life, but none from age 3 to 12 years of age.

5. Melissa's nutrition and hydration needs were addressed by the health care team by increasing her caloric intake and improving her hydration. A picture taken when she was 12 years old shows that she had been consuming sufficient calories for growth. (A gastrostomy tube was not inserted because it had not yet been invented when Melissa was a young girl.)
6. Nocturnal positive pressure ventilatory support was initiated when Melissa was approximately 6 years of age because of nocturnal hypoventilation and the conflict between the use of calories for growth and breathing. The positive pressure support relieved her work of breathing and rested her muscles. In addition, it appeared to reverse forces that could contribute to pectus deformity of her anterior chest wall.

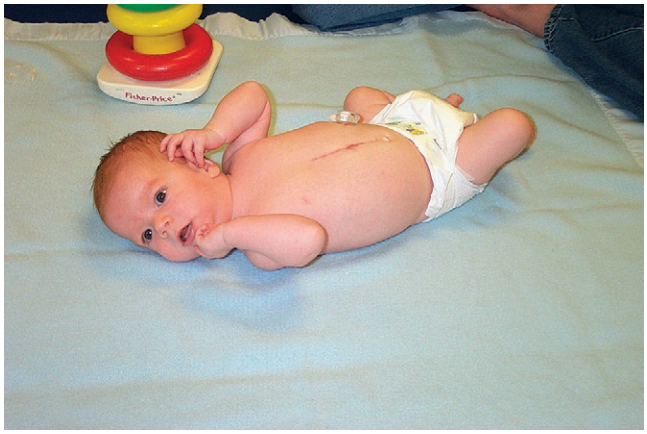


Fig. 39-17 Jonathan, 6 months of age. His severe gastroesophageal reflux required surgical support (gastrostomy tube and Nissen fundoplication procedures) at 5 months of age. His mother reports that his favorite posture when he is supine is extreme trunk extension and right head rotation. This is a typical compensatory strategy in response to the noxious stimulus of reflux and/or upper airway obstruction.

The same concept can be applied to other impairment categories. For example, in Katie's case, if her integumentary system showed connective tissue restrictions secondary to kyphoscoliosis, her integumentary system would be the primary limiting factor to improving pulmonary status rather than the neuromuscular system and internal organs. In other words, if Katie's ribcage could be mobilized but overlying taut skin disallowed movement, breathing strategies to increase her lung volumes would be ineffective. This is observed in patients who have connective tissue involvement such as in the case of scar formation, scleroderma, or severe burns. In these cases, the skin has insufficient mobility to allow the underlying muscles to move the chest wall. If the chest wall moves inadequately, lung volumes will not be sufficient to deliver sufficient oxygen to working muscle. The severity of the condition and damage to the integumentary and proximal underlying structures will determine the extent of impaired breathing mechanics.

Conditions related to the internal organs may have a subtle influence on postural control and breathing. Infants with severe gastroesophageal reflux, for example, may assume a posture of trunk hyperextension and right head rotation in supine (Sandifer's syndrome) (Figure 39-17).[63,69-72] Such posturing may be mistaken for a neuromuscular lesion. In fact, the infant may use this posturing to move away from the noxious stimulus of reflux experienced whenever he or she moves into a flexed trunk posture of head turning and lateral

trunk bending to the left. If the child is not assessed from a multisystem perspective, the physical therapist may focus on treating the excessive extensor tone and asymmetry of the trunk rather than the underlying cause of the motor behavior, which stems from the internal organs. If untreated, these infants may develop further spinal extension and upper thoracic breathing strategies to avoid exacerbating the reflux and increasing intraabdominal pressure. Reflux can be exacerbated with descent of the diaphragm onto an irritable stomach and by increased intraabdominal pressure. Over time, the infant may develop impairments in all motor systems, potentially affecting overall health and participation. For example, children with cystic fibrosis were traditionally tipped downward for postural drainage to improve lung function; however, this treatment predisposed many of these children to gastroesophageal reflux and a worsening of their pulmonary status.[73,74] The outline below describes how the motor systems could be affected by a pathology originating in the internal organs.

1. Internal organs: The pathology originates within these organs.
2. Neuromuscular system: Inadequate motor control of trunk flexors, necessary for balance, forced expiratory maneuvers, and lumbar stabilization, may develop. Pathology of the internal organs may predispose the child at a later stage to low back dysfunction and pain because normal positive pressure stabilization motor strategies, especially from the diaphragm and abdominal muscles, are not developed in childhood.
3. Musculoskeletal system: Sequelae of associated pathology may include (a) excessive ligamentous shortening of lumbar vertebrae secondary to the chronic lordotic posture and/or (b) elevated ribcage alignment, which results when the trunk flexors do not actively engage in pulling the ribcage inferiorly and the over-recruitment of upper accessory muscles continues to promote this position, which can contribute to (c) increased risk for low back pain secondary to poor lumbar stabilization strategies, weak abdominal muscles, and atypical vertebral alignment.
4. Cardiovascular and pulmonary systems: Limited overall endurance may result if the child develops an upper thoracic breathing pattern as his or her primary breathing pattern in response to the noxious feedback received in response to using the diaphragm as the primary respiratory muscle. This could also predispose the child to neck and shoulder dysfunction because the conflict between the respiratory recruitment of the upper accessory muscles and the dual role these muscles play in upper quadrant movement may contribute to overuse and later complaints of symptoms such as pain, fatigue, and headaches.
5. Integumentary system: This system is less commonly a contributor to motor impairments, but can be in cases such as surgical scars, where tight connective tissue in the skin restricts flexion of the trunk, shoulder, or hip.

Impaired breathing mechanics do not occur strictly because of a direct impairment of the lungs, airways, or chest wall muscles. Impaired breathing mechanics can occur from insults to any organ or system that influences motor performance. The cardiovascular and pulmonary systems should be seen as integral parts of motor assessment in order to determine whether the mechanics of breathing are facilitating or impairing the patient's overall motor performance. That is, breathing mechanics may be the cause or the consequence of motor dysfunction. A thorough multisystem evaluation helps the clinician distinguish the two. Respiratory muscle testing has a role in determining the degree to which impairments are respiratory or postural in origin.[75] With an analysis based on a Soda Can Model, the physical therapist can identify the sources of the underlying impairments and target interventions accordingly.

Summary

In this chapter, the role of respiratory mechanics as they relate to a range of body systems has been explored. Gravity was described as a major influence on both the potential movement of the chest wall and development of the chest wall, trunk, and thoracic structures. The dual role of the trunk to support both respiratory and postural control was introduced in the context of the Soda Can Model. Clinical cases based on multiple motor impairment categories were described to illustrate how trunk control, breathing, and internal organ function depend on the ability of the body to generate, maintain, and regulate pressure in the thoracic and abdominal cavities, the control of which extends from the vocal folds down to the pelvic floor. In the clinical examples, the five motor impairment categories—musculoskeletal, neuromuscular, cardiovascular and pulmonary, and integumentary systems and the internal organs—were screened with respect to their roles in motor performance and breathing mechanics; each system influences the performance of the others. Such analysis provided the basis for designing treatment plans that targeted the primary impairments. Anticipated motor outcomes involving the trunk and breathing were achieved.

Review Questions

1. Explain the role of gravity in normal chest wall development of infants.
2. Explain how the pressures in the thorax and abdomen provide postural support for the trunk and the role of the diaphragm in that process.
3. Explain the role of the vocal folds and the pelvic floor in normal respiration and in high postural demanding activities.
4. Explain the relationship between the gastrointestinal system and respiration.
5. Using one of your patients as a case study, apply the concepts of multisystem evaluation, examination, and intervention planning as discussed in this chapter.

References

1. APTA: Guide to Physical Therapist Practice, ed 2. *Physical Therapy* 81, 2001.
2. Panitch HB: The pathophysiology of respiratory impairment in pediatric neuromuscular diseases. *Pediatrics* 123(Suppl 4):S215–S218, 2009.
3. Inal-Ince D, Savci S, Arikan H, et al: Effects of scoliosis on respiratory muscle strength in patients with neuromuscular disorders. *Spine J* 9(12):981–986, 2009.
4. Coonan TJ, Hope CF: Cardio-respiratory effects of change in body position. *Canadian Anaesthetists' Society Journal* 30:424–437, 1983.
5. Piper MC, Darrah J: *Motor assessment of the developing infant*, Philadelphia, 1994, Sanders.

6. Bach JR, Bianchi C: Prevention of pectus excavatum for children with spinal muscular atrophy type 1. *American Journal of Physical Medicine and Rehabilitation* 82:815–819, 2003.
7. Lissoni A, Aliverti A, Tzeng AC, et al: Kinematic analysis of patients with spinal muscular atrophy during spontaneous breathing and mechanical ventilation. *American Journal of Physical Medicine and Rehabilitation* 77:188–192, 1998.
8. Papastamelos C, Panitch HB, Allen JL: Chest wall compliance in infants and children with neuromuscular disease. *American Journal Respiratory Critical Care Medicine* 154:1045–1048, 1996.
9. West JB: *Pulmonary pathophysiology: the essentials*, ed 7, Philadelphia, 2008, Lippincott Williams and Wilkins.
10. Toder DS: Respiratory problems in the adolescent with developmental delay. *Adolescent Medicine* 11:617–631, 2000.
11. Massery MP: Chest development as a component of normal motor development: implications for pediatric physical therapists. *Pediatric Physical Therapy* 3:3–8, 1991.
12. Massery M: Theoretical model: The interaction and inter-dependence of breathing and postural control. Unpublished manuscript for doctoral classwork at Rocky Mountain University of Health Professions, Provo, UT:1–15, 2003.
13. Massery M: Musculoskeletal and neuromuscular interventions: a physical approach to cystic fibrosis. *Journal of the Royal Society of Medicine* 98(Supplement 45):55–66, 2005.
14. Hodges PW, Gandevia SC: Activation of the human diaphragm during a repetitive postural task. *Journal of Physiology* 522:165–175, 2000.
15. Hudson AL, Butler JE, Gandevia SC, et al: Interplay between the inspiratory and postural functions of the human parasternal intercostal muscles. *J Neurophysiol* 103(3):1622–1629, 2010.
16. Hodges PW, Cresswell AG, Thorstensson A: Intra-abdominal pressure response to multidirectional support-surface translation. *Gait Posture* 20(2):163–170, 2004.
17. Morris SL, Allison GT: Effects of abdominal muscle fatigue on anticipatory postural adjustments associated with arm raising. *Gait Posture* 24(3):342–348, 2006.
18. Rehan VK, McCool FD: Diaphragm dimensions of the healthy term infant. *Acta Paediatr* 92(9):1062–1067, 2003.
19. Dimitriou G, Greenough A, Kavvadia V, et al: Diaphragmatic function in infants with surgically corrected anomalies. *Pediatr Res* 54(4):502–508, 2003.
20. Hodges PW, Gurfinkel VS, Brumagne S, et al: Coexistence of stability and mobility in postural control: evidence from postural compensation for respiration. *Experimental Brain Research* 144:293–302, 2002.
21. Smith MD, Russell A, Hodges PW: Disorders of breathing and continence have a stronger association with back pain than obesity and physical activity. *Australian Journal of Physiotherapy* 52(1):11–16, 2006.
22. Hodges PW, Sapsford R, Pengel LHM: Postural and respiratory functions of the pelvic floor muscles. *Neurourology & Urodynamics* 26(3):362–371, 2007.
23. Orlikoff RF: Voice production during a weightlifting and support task. *Folia Phoniatrica et Logopedica* 60(4):188–194, 2008.
24. Flaminiano LE, Celli BR: Respiratory muscle testing. *Clinics in Chest Medicine* 22:661–677, 2001.
25. De Troyer A, Kirkwood PA, Wilson TA: Respiratory action of the intercostal muscles. *Physiol Rev* 85(2):717–756, 2005.
26. De Troyer A, Leduc D: Role of pleural pressure in the coupling between the intercostal muscles and the ribs. *J Appl Physiol* 102(6):2332–2337, 2007.
27. Butler JE, Gandevia SC: The output from human inspiratory motoneuron pools. *Journal of Physiology* 586(5):1257–1264, 2008.
28. Hodges PW, Heijnen I, Gandevia SC: Postural activity of the diaphragm is reduced in humans when respiratory demand increases. *Journal of Physiology* 537:999–1008, 2001.
29. Grimstone SK, Hodges PW: Impaired postural compensation for respiration in people with recurrent low back pain. *Experimental Brain Research* 151:218–224, 2003.
30. Gandevia SC, Butler JE, Hodges PW, et al: Balancing acts: respiratory sensations, motor control and human posture. *Clinical and Experimental Pharmacology and Physiology* 29:118–121, 2002.
31. Bach JR, Baird JS, Plosky D, et al: Spinal muscular atrophy type 1: management and outcomes. *Pediatric Pulmonology* 34:16–22, 2002.
32. Wilson TA, Legrand A, Gevenois PA, et al: Respiratory effects of the external and internal intercostal muscles in humans. *Journal of Physiology* 530:319–330, 2001.
33. De Troyer A, Gorman RB, Gandevia SC: Distribution of inspiratory drive to the external intercostal muscles in humans. *Journal of Physiology* 546:943–954, 2003.
34. Ratnovsky A, Elad D, Halpern P: Mechanics of respiratory muscles. *Respiratory Physiology & Neurobiology* 163:82–89, 2008.
35. Canavan PK, Cahalin L: Integrated physical therapy intervention for a person with pectus excavatum and bilateral shoulder pain: a single-case study. *Arch Phys Med Rehabil* 89(11):2195–2204, 2008.
36. Skjodt NM, Farran RP, Hawes HG, et al: Simulation of acute spinal cord injury: effects on respiration. *Respiratory Physiology* 127:3–11, 2001.
37. Hodges PW, Gandevia SC: Changes in intra-abdominal pressure during postural and respiratory activation of the human diaphragm. *Journal of Applied Physiology* 89:967–976, 2000.
38. Serway R, Faughn J: *College physics*, Orlando, Fla, 1992, Harcourt Brace Jovanovich.
39. Schilero, G. J., Spungen AM, Bauman WA, et al: Pulmonary function and spinal cord injury. *Respir Physiol Neurobiol* 166(3):129–141, 2009.
40. Mason RJ, Broaddus VC, Martin T, et al: *Murray and Nadel's Textbook of Respiratory Medicine*, ed 5, Philadelphia, 2010, Elsevier.
41. Spahija, J, de Marchie M, Grassino A: Effects of imposed pursed-lips breathing on respiratory mechanics and dyspnea at rest and during exercise in COPD. *Chest* 128(2):640–650, 2005.
42. Pierce RJ, Worsnop CJ: Upper airway function and dysfunction in respiration. *Clinical and Experimental Pharmacology and Physiology* 26:1–10, 1999.
43. Deem JF, Miller L: *Manual of voice therapy*, ed 2, Austin, Tex, 2000, PRO-ED, Inc.
44. Irwin RS, Boulet LP, Cloutier MM, et al: Managing cough as a defense mechanism and as a symptom. A consensus panel report of the American College of Chest Physicians. *Chest* 114:133–181, 1998.
45. Bach JR, Saporito LR: Criteria for extubation and tracheostomy tube removal for patients with ventilatory failure. A different approach to weaning. *Chest* 110:1566–1571, 1996.
46. Borowitz SM, Borowitz KC: Gastroesophageal reflux in babies: impact on growth and development. *Infants and Young Children* 10:14–26, 1997.
47. Borowitz SM, Sutphen JL: Recurrent vomiting and persistent gastroesophageal reflux caused by unrecognized constipation. *Clinical Pediatrics* 43:461–466, 2004.
48. Iannaccone ST: Modern management of spinal muscular atrophy. *Journal of Child Neurology* 22(8):974–978, 2007.
49. Corcia, P, Meininger V Management of amyotrophic lateral sclerosis. *Drugs* 68(8):1037–1048, 2008.
50. Hayama S, Honda K, et al: Air trapping and arboreal locomotor adaptation in primates: a review of experiments on humans. *Zeitschrift fur Morphologie und Anthropologie* 83:149–159, 2002.
51. Hagins M, Lamberg EM: Natural breath control during lifting tasks: effect of load. *European Journal of Applied Physiology* 96(4):453–458, 2006.
52. Massery M: *The effect of airway control on postural stability (doctoral dissertation)*. Provo, UT, Rocky Mountain University of HealthProfessions, 2011.
53. Hoit JD, Banzett RB, Brown R: Binding the abdomen can improve speech in men with phrenic nerve pacers. *American Journal of Speech-Language Pathology* 11(1):71–76, 2002.
54. Wadsworth B, Haines TP, Cornwell PL, et al: *The effect of an abdominal binder on respiratory function and voice in people with acute tetraplegia*. The Australian Physiotherapy Annual Conference. Sydney, Australia, 2009.
55. Mandell DL, Arjmand EM: Laryngomalacia induced by exercise in a pediatric patient. *International Journal of Pediatric Otorhinolaryngology* 67(9):999–1003, 2003.
56. Sapsford RR, Hodges PW, Richardson CA, et al: Co-activation of the abdominal and pelvic floor muscles during voluntary exercises. *Neurourology and Urodynamics* 20:31–42, 2001.
57. Button BM, Sherburn M: Cough and the pelvic floor: prevent, control and treat urinary incontinence. *Pediatric Pulmonology, Supplement* 31:114 –115, 2008.
58. Langman H, Orr A, et al: Urinary incontinence in CF: why does it happen? Eighteenth Annual North American Cystic Fibrosis Conference, St. Louis, Mo. *Pediatric Pulmonology* 27(Suppl):154–155, 2004.
59. Dodd ME, Langman H: Urinary incontinence in cystic fibrosis. *Journal of The Royal Society of Medicine* 98(Suppl 45):28–36, 2005.
60. De Looze D, Van Laere M, De Muynck M, et al: Constipation and other chronic gastrointestinal problems in spinal cord injury patients. *Spinal Cord* 36:63–66, 1998.
61. Noreau L, Proulx P, Gagnon L, et al: Secondary impairments after spinal cord injury: a population-based study. *American Journal of Physical Medicine and Rehabilitation* 79:526–535, 2000.
62. Zimmer MB, Nantwi K, Goshgarian HG: Effect of spinal cord injury on the respiratory system: basic research and current clinical treatment options. *Journal of Spinal Cord Medicine* 30:319–330, 2007.

63. Frankel EA, Shalaby TM, Orenstein SR: Sandifer syndrome posturing: relation to abdominal wall contractions, gastroesophageal reflux, and fundoplication *Digestive Diseases & Sciences* 51(4):635–640, 2006.
64. Bhatia J, Parish A: GERD or not GERD: the fussy infant. *J Perinatol* 29(Suppl 2):S7–11, 2009.
65. Massery M: Asthma: multisystem implications. In Campbell S, Palisano R, Vander Linden D, Editors: *Physical therapy for children*, Philadelphia, Pa: WB. Saunders, 2005.
66. Lanini B, Bianchi R, Romagnoli I, et al: Chest wall kinematics in patients with hemiplegia. *American Journal of Respiratory and Critical Care Medicine* 168:109–113, 2003.
67. McNamara D: *Diaphragmatic Hernia Survivors Do Well. Chest Physician*, Morristown, NJ, 2011, Elsevier, Inc. for The American College of Chest Physicians. 6: 1 & 5.
68. Sobus KML, Horan SM, et al: Respiratory management of neuromuscular diseases in children. *Physical Medicine and Rehabilitation: State of the Art Reviews* 14:285–299, 2000.
69. Lehwald N, Krausch M, Franke C, et al: Sandifer syndrome—a multidisciplinary diagnostic and therapeutic challenge. *European Journal of Pediatric Surgery* 17:203–206, 2007.
70. Demir E, Saka E, Aysun S: A case of Sandifer's syndrome with hand tremor. *Turkish Journal of Pediatrics* 43:348–350, 2001.
71. de Ybarrondo L, Mazur JL: Sandifer's syndrome in a child with asthma and cerebral palsy. *Southern Medical Journal* 93(10):1019–1021, 2000.
72. Kostakis A, Manjunatha NP, Kumar A: Abnormal head posture in a patient with normal ocular motility: Sandifer syndrome *Journal of Pediatric Ophthalmology & Strabismus* 45(1):57–58, 2008.
73. Button BM, Heine RG, Catto-Smith AG, et al: Chest physiotherapy in infants with cystic fibrosis: to tip or not? A five-year study. *Pediatric Pulmonology* 35:208–213, 2003.
74. Button BM, Heine RG, Catto-Smith AG, et al: Chest physiotherapy, gastro-esophageal reflux, and arousal in infants with cystic fibrosis. *Archive of Diseases in Childhood* 89:435–439, 2004.
75. Nicot F, Hart N, Forin V, et al: Respiratory muscle testing: a valuable tool for children with neuromuscular disorders. *American Journal of Respiratory and Critical Care Medicine* doi:10.1164/rccm.200512-1841OC, 2006.