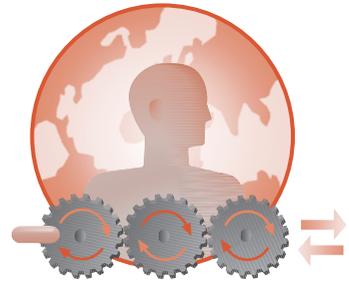


C H A P T E R 3 9

Multisystem Consequences of Impaired Breathing Mechanics and/or Postural Control



Mary Massery

KEY TERMS

Abnormal or compensatory breathing patterns
 Abdominal binder
 Breathing mechanics
 Gastrointestinal impairments
 Gravity's influence on development
 Integumentary impairments
 Internal organs
 Multisystem interactions
 Musculoskeletal impairments
 Neuromuscular impairments

Normal and abnormal development of chest wall
 Paradoxical breathing
 Pelvic floor
 Postural control
 Reflux
 Sandifer's syndrome
 Scoliosis
 Soda-pop can model of respiratory and postural control
 Spinal cord injury
 Vocal folds

The cardiovascular/pulmonary (CP) system is unique in that it provides both physiological support (oxygen delivery) as well as a mechanical support (respiratory/trunk muscle control) for movement. The physiological components have been covered extensively in other sections of this book. This chapter focuses on the mechanical aspect of ventilation and its interactions with other body systems in both health and dysfunction and includes three major points of focus:

1. Breathing is a three-dimensional motor task that is influenced by gravity in all planes of motion.
2. Breathing is an integral part of multisystem interactions and consequences that simultaneously support respiration and postural control for all 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, will be

incorporated into this chapter (APTA, 2001). An additional fifth category, the internal organ (IO) system, is added by this author (Box 39-1). In addition to addressing the impact of these impairment categories on health and motor performance from a ventilatory viewpoint, this author also presents a method to cross-check impairment-based findings with functional limitations. Six everyday functional tasks that require the integration of breathing and movement are presented (Box 39-2).

BREATHING: A THREE-DIMENSIONAL ACTIVITY WITHIN GRAVITY'S INFLUENCE

Planes of Ventilation and Gravity's Influence

Ventilation does not take place in a one-dimensional plane but rather as a three-dimensional activity. During every breath, the chest has the potential to expand in an anterior-posterior

BOX 39-1**Motor Impairment Categories**

1. Neuromuscular (NM) system
2. Musculoskeletal (MS) system
3. Integumentary (INT) system
4. Cardiovascular/pulmonary (CP) system
5. Internal organs (IO) system, especially gastrointestinal system*

*IO system added by Massery.

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

BOX 39-2**Daily Tasks that Require the Integration of Respiratory and Postural Demands of the Trunk for Function**

1. Breathing
2. Coughing
3. Sleeping
4. Eating
5. Talking
6. Moving

plane, an inferior-superior plane, and a lateral plane (Figure 39-1). This means that the muscles that support breathing are resisted by gravity in one direction, assisted by gravity in another direction, and relatively unaffected in other directions. For example, in an upright position, superior expansion of the chest is resisted by gravity while inferior expansion is assisted, and other movements of the chest (lateral, anterior, and posterior expansion) are relatively unaffected by gravity. The adverse effects of gravity are counteracted by muscles that can function even with the resistance of gravity. If the respiratory muscles become dysfunctional through weakness, paralysis, fatigue, or some other condition, the patient may no longer be able to breathe effectively within gravity's influence. Therefore, positioning of patients with impaired breathing mechanics must take into consideration how gravity will affect the muscles that support breathing in any particular posture.

Effects of Gravity on Normal and Abnormal Chest Wall Development

Gravity also plays an extremely crucial role in the skeletal development of the chest in the newborn. Normally-developing infants move freely in and out of postures, such as prone, hands-knees, and standing, as they progress developmentally, allowing gravity to alternately assist or resist the movements. Moving through these postures, the infant strengthens and develops muscle groups and learns to interact with the gravitational force in his or her environment (Bly, 1994). The

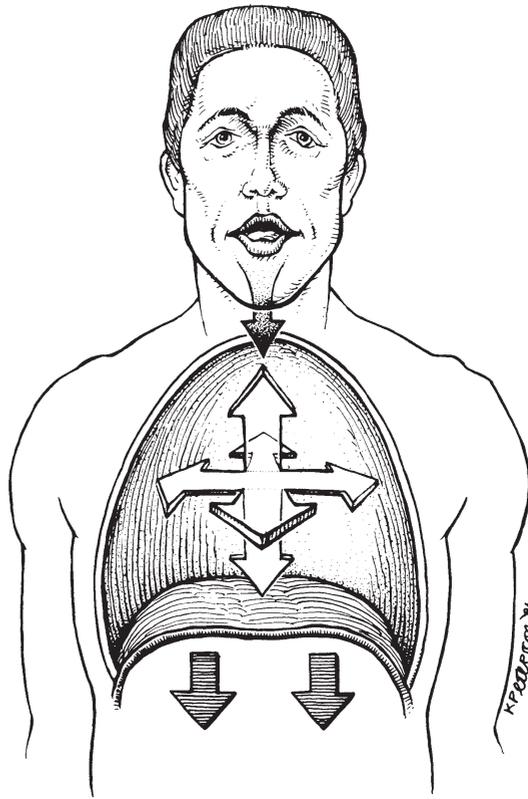


FIGURE 39-1 Planes of respiration: anterior-posterior, inferior-superior, and lateral.

combination of normal movement patterns experienced within a gravitational field and genetic predisposition influences the normal development of the bones, muscles, and joints that comprise the thoracic cage (ribcage) and thoracic spine. Infants with limited ability to move within their environment and limited ability to counteract the force of gravity develop atypical joint alignment and atypical muscle support that may lead to impaired breathing mechanics or vice versa (Bach, 2003; Lissoni et al, 1998; Papastamelos, 1996). Severe neuromuscular (NM) deficits such as cerebral palsy, spinal muscle atrophy, cerebral vascular accidents, head traumas, and spinal cord injuries are examples of conditions that can cause such a muscle imbalance in children. Muscle weakness or fatigue of the trunk muscles can also be caused by conditions arising outside of the NM system, such as oxygen transport deficits from bronchopulmonary dysplasia (BPD), congenital heart defects, etc., or from nutritional deficits such as gastroesophageal reflux, absorption problems, etc. Therefore, a variety of reasons may account for an infant's inability to change his or her own positions in space. Impairments to breathing mechanics may be caused by muscle weakness, muscle tone problems such as hypertonicity or hypotonicity, motor planning deficits, motor learning deficits, and/or medical fragility (Toder, 2000).

Children with breathing mechanics impairment typically spend significantly more time in a supine posture than in any



FIGURE 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 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.



FIGURE 39-3 A and B, Newborn chest. Note triangular shape, short neck, narrow and flat upper chest, round barreled lower chest. Muscle tone is primarily flexion and breathing is primarily diaphragmatic and on one plane: inferior.

other posture, which can lead to unbalanced gravitational influence and undesirable changes in the thorax. These deformities may include retaining the more primitive triangular shape of the newborn chest (Figure 39-2, A). In some cases, the child's diaphragm remains functional yet unbalanced by weak or paralyzed abdominal and intercostal muscles, and this has a significant affect on the developing skeleton (Figure 39-2, B). Pronounced muscle imbalance of the trunk can result in such severe chest wall deformities that it impairs the child's ability to meet his or her ventilatory needs. Common musculoskeletal (MS) abnormalities are anteriorly flared lower ribs; a dynamic cavus deformity, likely a pectus excavatum or less often a pectus carinatum; laterally flared ribs and/or asymmetry (Figure 39-2, B, C, D) (Bach, 2003; Papastamelos, 1996; Massery, 1991). These deformities may be more devastating in one posture than another because of the child's unequal inability to counteract gravity's force.

Understanding normal chest wall development is essential for accurately assessing abnormal chest deformities seen in children (Massery, 1991). Initially the newborn's chest is triangular: narrow and flat in the upper portion and wider and more rounded in the lower portion (Figure 39-3). The infant's short neck renders the upper accessory muscles nonfunctional as ventilatory muscles. The infant's arms are held in flexion and adduction across the chest, significantly hampering lateral or anterior movement of the chest wall. The infant, forced to be a diaphragmatic breather, shows greater development of the lower chest and this leads to the triangular shaping of the ribcage. Newborns breathe primarily on a single plane of motion, inferior, rather than the three dimensions of the adult.

From three to six months of age the infant begins to develop more trunk extension tone and spends more time in a prone position on his or her elbows. The baby begins to reach



FIGURE 39-4 Infant chest wall at three to six months of age. Increased upper chest width. More convex shaping of entire chest as antigravity movements are becoming possible. Still has a short neck and two functionally separate chambers: thorax and abdomen.

out into the environment with his or her upper extremities. This facilitates development of the anterior upper chest. Constant stretching and upper extremity weight bearing helps to expand the anterior upper chest both anteriorly and laterally, while increasing posterior stabilization (Bly, 1994).



FIGURE 39-5 Infant chest wall at six to 12 months of age. The infant spends more time in 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 chest level, and the postural stabilization potential needed for more complex motor tasks. Note that the base of the ribcage is no longer barrel shaped like it is in the newborn.

An increase in intercostal and pectoralis muscle strength improves the infant's ability to counteract the force of gravity on the anterior upper chest in the supine position, leading to the development of a slight convex configuration of the area and a more rectangular shaping of the thorax from a frontal plane (Figure 39-4). The baby begins to breathe in more than one plane of motion.

The next significant development occurs when the child begins to independently assume erect postures (e.g., sitting, kneeling, or standing). Until this time, the ribs are aligned relatively horizontally, with narrow intercostal spacing (see Figure 39-3). The newborn's chest only comprises approximately one third of the total trunk cavity. As the child begins to consistently move up against the pull of gravity, the ribs, with the aid of the abdominal muscles and gravity, rotate downward (more so in the longer lower ribs), creating the sharper angle of the ribs (Figure 39-5). This markedly elongates the ribcage until it eventually occupies more than half of the trunk cavity (Figure 39-6). A comparison of chest x-rays of newborns and adults, as well as pictures of infants, clearly shows these developmental trends (Figure 39-7, A, B), which are summarized in Table 39-1.



FIGURE 39-6 A four-year-old boy. Note the elongated chest, 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 from a frontal view, and the elliptical shaping of the chest from a transverse view.

Optimum respiratory function cannot be expected from a severely underdeveloped or deformed chest and/or spine. As long as the condition that caused the trunk muscle imbalance persists, regardless of whether that deficit was a true NM disorder or an impairment in another motor impairment category (see Box 39-1), the chest wall and spine will likely develop abnormally. Frequent position changes, management of adverse NM tone, facilitation of weakened chest muscles, promotion of optimal breathing patterns, incorporation of ventilatory strategies with movement, as well as integration of physical therapy goals within the child's overall development and medical program, will stimulate the optimal chest and trunk development.

MULTISYSTEM INTERACTIONS AND THEIR INFLUENCE ON HEALTH AND MOTOR PERFORMANCE: THE RELATIONSHIP BETWEEN RESPIRATION AND POSTURAL CONTROL

A single body system acting in isolation does not produce normal movement. Every person is composed of multiple body systems that interact and overlap in duty: the summed interaction results in normal movement. If these interactions are not normal or adequately compensatory in nature, then motor impairments may result. Because of this, this author suggests that every physical therapy examination and evaluation should include a multisystem screening of all five impairment categories (see Box 39-1) in order to determine

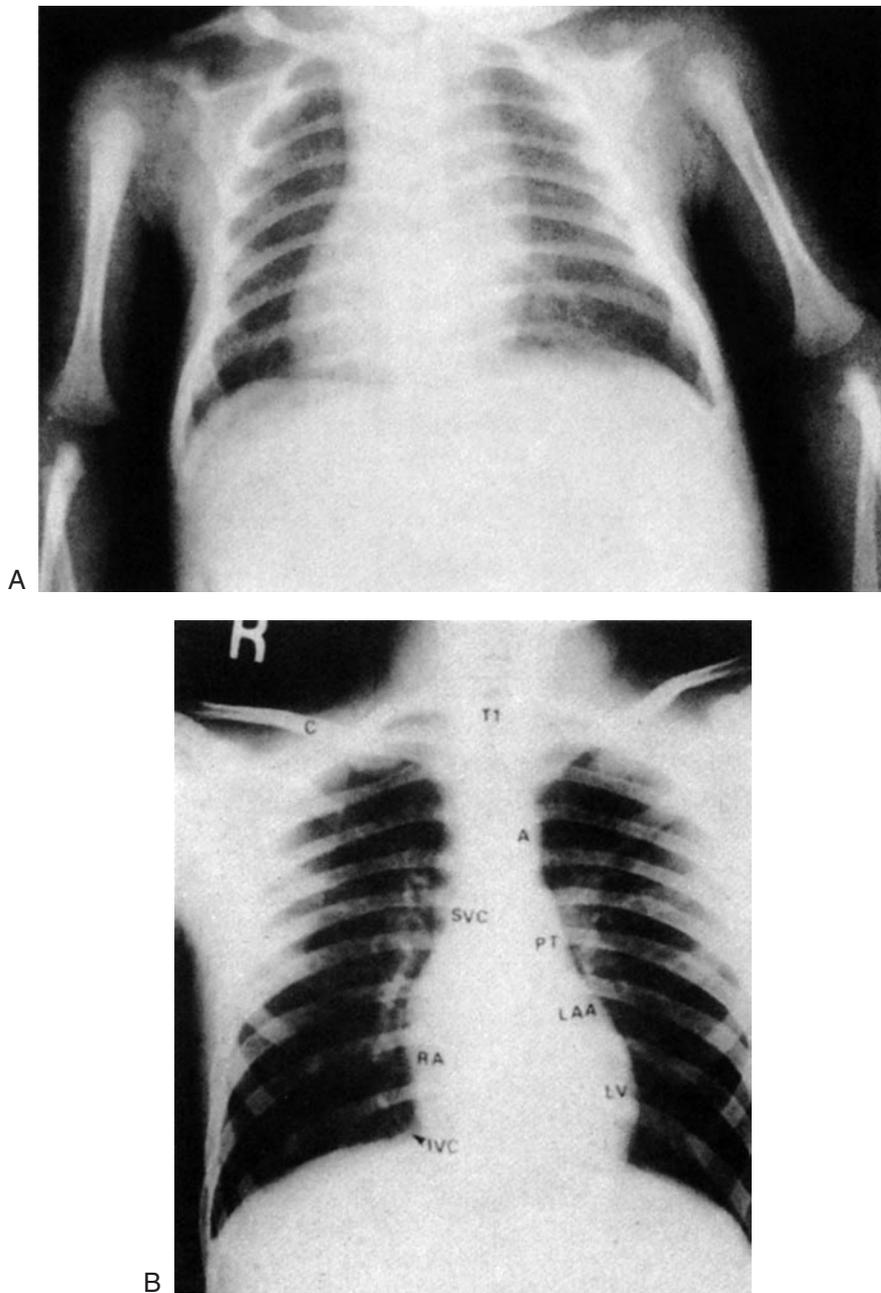
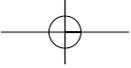


FIGURE 39-7 A, Newborn chest x-ray. Note triangular shaping of ribcage and narrow intercostal spacing. B, Normal adult chest x-ray. Chest shape is rectangular, ribs angled downward, upper and lower chest equally developed.

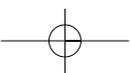


TABLE 39-1

Trends of Normal Chest Wall Development from Infant to Adulthood

CHEST	INFANT	ADULT
Size	Thorax occupies one third trunk cavity	Thorax occupies more than half trunk cavity
Shape	Triangular frontal plane, circular A-P plane	Rectangular frontal plane, elliptical A-P plane
Upper chest	Narrow, flat apex	Wide, convex apex
Lower chest	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 trunk	Wide, allows for individual movement of ribs and spine
Diaphragm	Adequate, minimal dome shape	Adequate, large dome shape
Accessory muscles	Nonfunctional	Functional

the impact of each body system on total motor performance. The following Soda-Pop Can model of respiratory and postural control was developed by this author to aide the reader in understanding the multisystem interactions between the mechanics of breathing and the simultaneous needs of postural control in both pediatric and adult populations.

Soda-Pop Can Model of Respiratory and Postural Control

Muscles of respiration are also muscles of postural support, and vice versa. Every muscle that originates or inserts onto the trunk is both a respiratory and postural muscle. This duality of function means that respiration and postural control can never be evaluated as isolated responses. External and internal forces that affect the function of the respiratory muscles will also affect postural responses. The Soda-Pop Can model seeks to illustrate this dual purpose.

Structurally Weak, Yet Functionally Strong

The shell of a soda-pop can is made out of a thin, flimsy aluminum casing that is easily smashed when empty. However, this same can, when it is full and unopened, 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, however, by flipping open the pop-top or inadvertently puncturing the side of the can, it loses its functional strength. It is no longer capable of counteracting the positive pressure forces that act upon it. Once opened, it is possible to completely smash the can into a tiny fragment of its original shape (Figure 39-8, B).

The trunk of the body uses a concept similar to the soda-pop can to prevent being “smashed” by external forces. The skeletal support of the trunk is not inherently strong. The spine and ribcage alone are not capable of maintaining their alignment against gravity without the muscular support that gives them the capability of generating pressures that can withstand the compressive forces of gravity. This is demonstrated daily by patients in intensive care unit (ICU)

settings. Weakened from prolonged illnesses and/ or medical procedures, patients in the ICU typically slump into a forward, flexed posture when they sit up for the first time, showing impaired ability to generate adequate pressure support through muscle activation to support an ideal alignment of the spine and ribcage in an upright posture. In pediatrics, the results can be even more alarming. Melissa, who suffered a C5 spinal cord injury during a vaginal birth injury, shows a complete collapse of the ribcage and spine in upright. Melissa was incapable of taking a single effective inspiratory effort in this posture, which explains why she had no tolerance for upright activities. Her soda-pop can was crushed, and with it her breathing mechanics (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 inside, resulting in positive pressure pushing outwardly upon the can, thus providing dynamic support to the metal. Likewise, the trunk of the body is composed of thoracic and abdominal chambers that are dynamically supported by muscle contractions to provide positive pressure in both chambers for respiratory and postural support.

The thoracic and abdominal chambers are completely 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 upon them by outside forces in order to support the “flimsy” skeletal shell. The primary muscles involved in this support are the intercostal muscles, which generate and maintain pressure for the thoracic chamber; the abdominal muscles, which generate and maintain pressure for the abdominal chamber, especially the transverse abdominus; the diaphragm, which regulates and uses the pressure in both chambers; and the back extensors, which provide stabilizing forces for the alignment of the spine and articulation with the



FIGURE 39-8 Soda-Pop Can model of respiratory and postural control. **A**, A soda-pop can derives its functional strength because the internal pressure of the carbonated drink is higher than the atmospheric pressure acting upon it, not because of its thin aluminum shell. **B**, Without the internal pressure support, the aluminum can is easily deformed and compressed. **C**, Melissa, age three-and-a-half years: C5 complete spinal cord injury due to birth trauma. Clinical example of a crushed trunk resulting in severely compromised respiratory mechanics in spite of the fact that her lungs are normal. Melissa was incapable of generating adequate positive pressures to counteract the constant force of gravity and atmospheric pressure upon her developing skeletal frame.

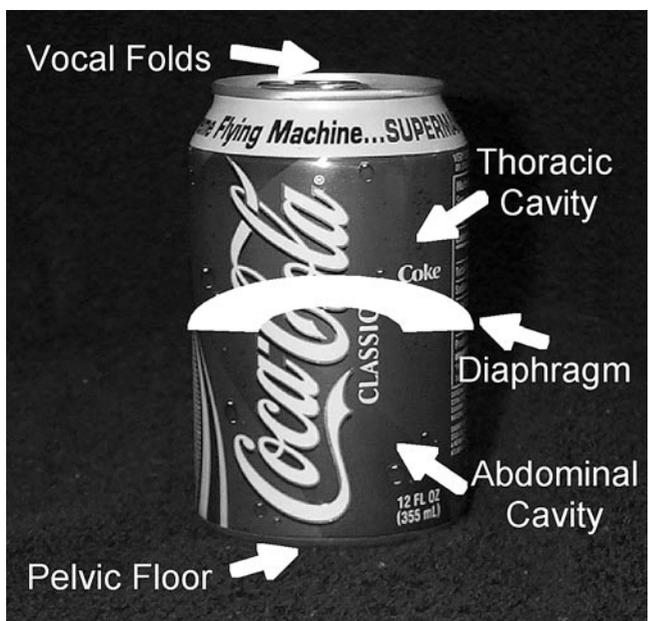


FIGURE 39-9 A soda-pop can as a three-dimensional model for trunk muscle support for breathing and postural control. Note that the control of pressure begins at the level of the vocal folds and extends all the way down to the pelvic floor. A breach in pressure anywhere along the cylinder will impair the total function of the can, and likewise for the patient's trunk.

ribcage. These muscles work synergistically to adjust the pressure in both chambers so that the demands of ventilation and posture are simultaneously met (Primiano, 1982; McGill, Sharratt & Seguin, 1995; Bouisset & Duchene, 1994; Rimmer et al, 1995; Bach, 2002; Faminiano & Celli, 2001).

A quick synopsis of the biomechanics of breathing will illustrate the normal interaction among the diaphragm, intercostals, and abdominals within the construct of a positive pressure chamber (Flaminiano & Celli, 2001; Cala, 1993; Nava et al, 1993; Rimmer & Whitelaw, 1993). The diaphragm is well known as the primary respiratory muscle, but this author asks the reader to see the diaphragm instead as a pressure regulating muscle. The diaphragm completely separates the thoracic cavity from the abdominal cavity and as such is capable of creating and utilizing pressure differences in the chambers to support the simultaneous needs of respiration and trunk stabilization. It is the interactions among the diaphragm, intercostals, and abdominal muscles, in addition to support from other trunk muscles, that work together to generate, regulate, and maintain thoracic and abdominal chamber pressures necessary for the ongoing, concurrent needs of breathing and motor control of the trunk (Hodges et al, 2001). The support works both ways: the diaphragm is dependent on the support of the intercostal and abdominal muscles for effective and efficient breathing, and likewise the trunk is dependent on the diaphragm to increase its muscular support and for increased pressure support during motor tasks with higher postural demands (Hodges et al, 2001; Grimstone

& Hodges, 2003; Hodges et al, 2002; Gandevia et al, 2002). One cannot be considered separate from the other.

When the diaphragm contracts to initiate inhalation, the central tendon descends inferiorly, creating negative pressure in the thoracic cavity and causing air to be drawn into the lungs due to the pressure differential with atmospheric pressure. Simultaneously, the intercostal muscles are activated to avoid being drawn inward toward the negative pressure (Lissoni et al, 1998; Rimmer et al, 1995; Wilson et al, 2001; De Troyer et al, 2003). Inadequate intercostal muscle support would cause the chest to collapse inward, eventual development of a MS deformity such as a pectus excavatum, and a secondary loss of chest wall compliance (see Figure 39-2, B) (Lissoni et al, 1998; Rimmer & Whitelaw, 1993; Skjodt et al, 2001; Han, et al 1993; Sumarez, 1986). While the diaphragm is descending, it creates positive pressure in the abdominal cavity due to the support of abdominal muscles, particularly the deepest muscle, the transverse abdominus (Hodges & Gandevia, 2000). The positive pressure created is equal to the negative pressure created in the thorax according to Newton's Law, which states that for every action, there is an equal and opposite reaction (Serway & Faughn, 1992). The diaphragm uses positive abdominal pressure like a fulcrum to stabilize the central tendon. This central stability then mechanically supports the effective contractions of the lateral (peripheral) fibers up and over the abdominal viscera (lateral and superior chest wall expansion) (Flaminiano, 2001).

The abdominal cavity has relatively higher pressure at rest than the thoracic cavity, as reflected by the natural positioning of the diaphragm within the trunk. Its dome is convex superiorly because the higher pressure from the abdominal cavity pushes it upward. During lung disease, this relationship of pressure may reverse and severely compromise the mechanics of breathing. For example, patients who have obstructive lung disease such as emphysema trap air distally in the diseased lung segments (Cherniack & Cherniack, 1983). Eventually the build up of air, as well as other aspects of the disease cause the thoracic cavity to become the higher pressure chamber at rest, pushing the diaphragm inferiorly until the dome of the diaphragm becomes flat. At that point, the diaphragm's mechanical support is so compromised that it can no longer function as an inspiratory muscle. To compensate, patients with end stage emphysema often lean forward on extended arms, flex their trunks, and activate their abdominal muscles to increase abdominal pressures and hopefully restore the correct pressure relationship with the thoracic chamber. If successful, they can temporarily push the dome of the diaphragm upward to give it a chance to function as an inspiratory muscle again and gain some relief from their constant dyspnea. This is an example of pathologic positive pressure support.

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

Vocal Folds and Vocal Apparatus. Normal positive thoracic pressure is needed for both postural support of the

upper trunk and for many expiratory maneuvers such as talking, coughing, and bowel and bladder evacuation (Pierce & Worsnop, 1999; Wood et al, 1986; Deem & Miller, 2000). The vocal folds and vocal apparatus provide the superior valve or pressure regulation of the thoracic chamber. If the vocal folds are compromised due to an impairment of the upper airway or because they are bypassed altogether with a tracheostomy or endotracheal tube, the patient becomes incapable of generating positive thoracic pressure support. Once the patient has inhaled maximally and reached pressure in the lungs equal to the pressure outside the lungs, the air will simply “fall out.” There is no valve at the top to hold the pressure inside the chest. Activities of the trunk that require positive pressure in the thorax will then be compromised. For example, without the vocal folds to regulate the controlled release of thoracic pressure during exhalation, there is no way for the patient to slowly, or eccentrically, release the air such as needed for talking or eccentric trunk or extremity activities. Thus, the therapist may notice speech and/or eccentric motor impairments. The same is true for concentric contractions. Without the vocal folds as the pressure valve, the patient can not build up adequate intrathoracic pressure to produce an effective cough (Bach & Saporito, 1996). Similarly, if the patient can not close the glottis and direct thoracic positive pressure downward toward the pelvic floor, then bowel and bladder evacuation may be compromised (Borowitz & Borowitz, 1997; Borowitz & Sutphen, 2004). For example, in the clinical setting, patients with tracheostomies are noted to often experience constipation, which improves as soon as they are decanulated and the vocal folds have been restored as an active component of trunk pressure regulation.

The patient with compromised vocal folds can generate a brief moment of positive expiratory pressures for activities such as coughing or yelling by learning to recruit a quick and forceful concentric contraction of the trunk flexors, primarily the abdominals, pectoralis and/or latissimus dorsi muscles immediately 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 normal opening of the vocal folds, and this causes a larger volume of air to be expelled per second. Unlike patients with obstructive lung disease who have an abnormally prolonged expiratory phase, patients with impairment to the pressure regulator at the top of the chamber have no natural mechanism to prolong exhalation either for eccentric or concentric motor tasks.

In addition to regulating the airflow out of the lungs, the vocal folds play an important role in generating the increased thoracic pressures needed for trunk stabilization associated with lifting, pushing, upper extremity weight bearing activity, etc (Hayama et al, 2002). This response is called the glottal effort closure reflex (Deem & Miller, 2000). The entire length of the vocal folds adducts and prevents any air leakage while the chest wall muscles and the abdominals contract to increase abdominal and thoracic pressures. This increased pressure stabilizes the shoulder complex to allow for greater

force production from the upper extremities. For example, a tennis player with a strong serve often uses a functional glottal effort closure reflex. The server throws the ball up while taking a deep breath in, then he or she closes the glottis at the peak of inspiration using the trapped air and the activation of the chest and abdominal muscles to increase thoracic pressure. Then, when the tennis racket makes contact with the ball, the server explosively expels the air (usually with a grunt) to maximize the force production of the serve. This concept is used by ordinary people on a daily basis to perform tasks such as pushing a heavy door open, lifting a heavy box, or leaning on a table with one arm and reaching across the table to pick something up with the other arm, and when an infant bears weight on his or her arms while crawling, etc. All these activities require the full or partial glottal effort closure response in order to increase the functional strength of the arms. This concept is consistent with the Soda-Pop Can model’s concept of pressure regulation for functional strength and control.

In pediatrics, the importance of the vocal folds as the superior pressure regulator may be observed in a child with a tracheostomy due to an airway impairment, or a child with poor vocal control for other reasons, without a NM diagnosis. The therapist may see that the infant crawls with elbow flexion rather than on extended arms, even though there is no muscle weakness in the arms. In this author’s clinical assessment, it may be the inability of the vocal folds to keep adequate positive pressure in the chest during weight bearing (glottal effort closure reflex) that 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 if it is present, will improve the child’s potential to meet the positive thoracic pressures necessary for higher level postural activities. In other words, working on restoring the trunk’s pressure support system (the soda-pop can) may result in greater functional gains than working on upper extremity exercises.

Other types of vocal fold interactions occur within this pressurized system to optimize speech, breathing, and/or postural control. For example, the vocal folds will have improved function as a speech valve if abdominal pressure is restored via an abdominal binder in patients with spinal cord injury (Hoit et al, 2002). Similarly, for children with laryngeal malacia or other types of upper airway obstructions, excessive inspiratory flow rates, which create excessive negative pressure in the upper airway, may result in decreased voicing or the appearance of exercise induced asthma (Mandell & Arjmand, 2003).

Pelvic Floor. The pelvic floor muscles provide support at the other end of the cylinder, at the base of the abdominal cavity. If there is dysfunction of these muscles, the abdominal cavity’s positive pressure potential will be adversely affected (Hodges & Gandevia, 2000). For example, when abdominal pressure is intended to be directed upward toward the vocal folds for coughing, sneezing, yelling, laughing, etc., insufficient pelvic floor musculature will result in a loss of positive

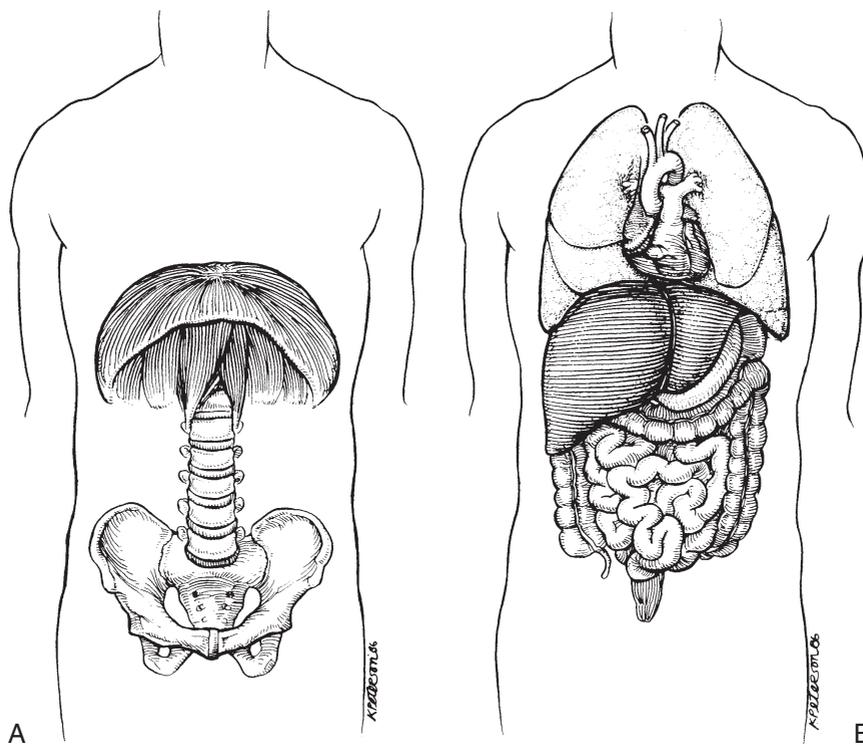


FIGURE 39-10 **A**, Note the diaphragm's position as the pressure regulator between the thoracic and abdominal cavities. **B**, Note the amount and alignment of the IOs within the trunk that are affected by the changes in the diaphragm's position during respiration.

pressure through the pelvic opening. This is often expressed as urinary stress incontinence, rendering the intended respiratory or postural maneuver less effective (Sapsford et al, 2001). There are numerous conditions that compromise the integrity of the pelvic floor, but the most obvious example is women who are postpartum. The overstretched pelvic floor muscles from childbirth cause them to inadvertently release positive pressure through the pelvic floor during demanding activities such as sneezing, coughing, and running. Women in this state learn to cross their legs or perform other pressure supporting compensatory behaviors to reduce urinary incontinence stresses while their pelvic floor heals. Other conditions, such as adult females with cystic fibrosis, experience a high incidence of urinary stress incontinence secondary to repetitive stress on the pelvic floor from the positive pressure associated with their chronic coughs (Langman et al, 2004; Dodd, 2004). Incontinence is not restricted to patients with primary pulmonary disease. Women with low back pain and impaired postural responses have also been noted to have a higher incidence of incontinence (Sapsford et al, 2001).

IOs. The organs in the trunk generate and/or use pressure changes in the thorax and abdomen to augment their own function. For example, the neuromuscular system creates the pressure changes in the thorax and abdomen. The lungs and esophagus use this pressure change in the thorax to create

efficient breathing and improved upper gastrointestinal motility. The cardiac system causes small changes in thoracic pressures. Using these changes and the changes from the respiratory mechanics, the heart and circulatory system can optimize blood circulation or blood pressure. The abdomen also uses pressure changes for its IOs. It uses the rhythmic pressures through the intestines for lumbar stabilization, improved lower gastrointestinal motility, optimal hemodynamic flow of body fluids, and optimal lymphatic drainage (Figure 39-10) (De Looze et al, 1998).

Without normal 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 IOs may be compromised. The dysfunction may be expressed as a drop in blood pressure (hypotension), inefficient respirations, gastroesophageal reflux, poor bladder emptying (increasing risk for urinary tract infections), or constipation, to name a few, during acute spinal cord injury where the ability to generate and use pressure support is immediately lost after the injury (De Looze et al, 1998; Noreau et al, 2000; Winslow & Rozovsky, 2003). These dysfunctions may not be caused solely by the lack of normal pressure support, but the lack of pressure support is a major cause of the dysfunction.

BOX 39-3**Compensatory Breathing Patterns Associated with Insufficient Muscular Support**

1. 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
2. Diaphragm and upper accessory breathing
 - a. Paralyzed or weak intercostals
3. Upper accessory muscles breathing
 - a. Paralyzed or weak diaphragm and intercostals; abdominal muscles may or may not be functional
4. Asymmetrical breathing
 - a. Paralyzed or weak trunk muscles on one side
 - b. Often associated with hemiparesis or scoliosis
5. 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
6. Shallow breathing
 - a. Small tidal volumes
 - b. Often associated with high NM tone or painful conditions



FIGURE 39-11 Nicholas, one year of age. Nicholas was born with both hemi-diaphragms 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 chest and falling abdomen during inhalation.

Summary

The Soda-Pop 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 IO function. When the patient has lost the ability to generate, regulate, and/or maintain appropriate internal pressures in both the thoracic and abdominal chambers, the mechanics of breathing, as well as numerous other body functions, may be impaired. Inadequate pressure support may start as an impairment to the mechanics of breathing, such as in a NM or MS disorder, or it may start as an impairment to another body system such as cardiovascular, pulmonary, airway, integumentary (INT), or the IOs but result in impaired breathing mechanics none the less. The overlapping of function precludes trunk motor performance from being accurately assessed in isolation of all other body systems, especially respiratory mechanics.

COMPENSATORY BREATHING PATTERNS ASSOCIATED WITH INSUFFICIENT MUSCULAR SUPPORT

As illustrated in the Soda-Pop Can model, the trunk muscles are needed to provide the necessary pressure changes for normal breathing. What happens if the muscles are weak, paralyzed, fatigued, or otherwise nonsupportive? What kinds of compensatory breathing patterns may develop? Six different compensatory breathing patterns are described herein (Box 39-3).

Paradoxical Breathing

Paradoxical breathing is named for the paradoxical movements of the chest noted during inspiration. It is sometimes clinically referred to as belly breathing, see-saw breathing, or reverse breathing. The first type of paradoxical breathing is caused by a strong contraction of the diaphragm in the absence of adequate muscular support from the two other triad muscles: the intercostal muscles and abdominal muscles. The diaphragm contracts, the abdomen rises excessively because inadequate abdominal muscle function does not stop the descent of the diaphragm with positive pressure, and the upper chest collapses because of a lack of the stabilizing contraction of the intercostal muscles (see Figure 39-2, A). This is the more common form of paradoxical breathing, and although it is not efficient, it is usually sufficient for breathing without mechanical ventilator support (Lissoni et al, 1998).

The second type of paradoxical breathing occurs when the diaphragm is weak or paralyzed while the upper accessory muscles are still intact. The abdominal muscles may or may not be functional. The inspiratory action now is opposite of the motion that was described for the first type (Figure 39-11). The abdomen is drawn inward toward the negative pressure in the thorax created by the upper accessory muscle during inhalation. Thus the chest rises and the belly falls. Generally this second type of paradoxical breathing requires at least part-time mechanical ventilation support because the accessory muscles are not designed to meet the needs of long-term independent ventilation and are more likely to fatigue and cause respiratory distress. The loss of the diaphragm as



FIGURE 39-12 Justin, nine 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.

the primary respiratory muscle results in a much greater inspiratory volume loss than the loss of just the accessory-muscles support noted in the first paradoxical pattern. Loss of the diaphragm as the primary pressure regulator for the trunk also results in significant deficits in postural control.

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

Another type of compensatory breathing pattern occurs when the intercostal and abdominal muscles are paralyzed or weak but the diaphragm and upper accessory muscles still function (i.e., patients with tetraplegia, high paraplegia, some congenital pectus excavatum deformities, upper airway obstructions, or asthma). These patients learn to 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, this compensatory breathing pattern prevents the collapse of the upper chest that is seen in paradoxical breathing. This must be cognitively coordinated with the inspiratory phase and is generally a more effective breathing pattern for patients with NM weakness but may not be an efficient choice for patients with asthma. On subjective breathing assessment, these patients often present with shortened neck muscles. Intercostal retractions, or the collapsing of the intercostal spaces on inspiration, may be seen here, especially at the level of the xiphoid. The paralyzed or weak intercostal muscle tissue will be sucked in toward the lungs during the creation of negative pressure within the chest, thus the observance of the intercostal retractions that in the long term can develop into a



A



B

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

pectus excavatum (Figure 39-12) (Bach & Bianchi, 2003; Massery, 2005).

Upper Accessory Muscles Only

If the patient lacks all of the “triad ventilatory muscles,” independent breathing can only be attempted using the upper accessory muscles in a superior plane and possibly some anterior expansion as well. Generally these patients will need mechanical ventilation to augment their independent effort because the lung volumes they can generate will not be adequate to support the oxygen needs of the body.



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

Asymmetrical Breathing

Patients with asymmetrical movement of the chest due to a cerebral vascular accident (CVA), a scoliosis, or other types of asymmetric impairments may demonstrate an asymmetric breathing pattern. This is generally sufficient for breathing without a mechanical ventilator because the strong side compensates for the weak side (Lanini et al, 2003). This compensation, however, may lead to asymmetric alignment of the trunk that adversely affects postural control in upright postures. In addition, the adverse effects on posture can lead to undesired MS changes over a prolonged period of time, especially for the pediatric patient. Prevention of these secondary changes is of utmost importance (Sobus et al, 2000) (Figure 39-13).

Lateral or Gravity Eliminated Breathing

Patients with generalized weakness, such as with benign hypotonia, prolonged illness, an incomplete spinal cord injury, etc., may show a tendency to breathe wherever gravity provides the least resistance. For example, in a supine position, patients with weakened chest muscles cannot effectively oppose the force of gravity in the anterior plane, thus they alter their breathing pattern to expand primarily in the lateral plane

where gravity is eliminated. In sitting, these same patients would tend to breathe inferiorly where gravity would assist the movement. Likewise, in a side-lying position they would tend to breathe in an anterior plane. Overall these patients have the best prognosis for effective breathing retraining methods because they have weakness, not complete paralysis.

Shallow Breathing

Shallow breathing typically results from injuries to the central nervous system resulting in high tone, such as Parkinson, head injuries, cerebral palsy, etc. It can also occur secondary to painful conditions such as low back pain. The breathing patterns are altered not so much by muscle weakness as by the following: chest immobility because of abnormally high NM tone (spasticity, rigidity, tremors), which severely limits chest expansion in any plane; cerebellar discoordination; improper sequencing because of lesions in the brain, most commonly seen with medullary lesions; or painful conditions that cause the patient to limit changes in trunk pressures in order to limit changing pressures on the MS lesion. The breathing pattern is usually symmetrical, shallow, sometimes asynchronous, and frequently tachypneic (respiratory rates over 25 breaths/min). Initiation and follow-through of a volitional maximal

TABLE 39-2

Identifying Katie's Motor Impairments from a Multisystem Model and Planning a Targeted Intervention Strategy

IMPAIRMENT CATEGORIES	MS	NM	CP	INT	IO
Identify primary pathology	Scoliosis				
Identify the progression of impairments	MS→	NM→	CP→	IO→	(INT)
List current impairment problems	<p>MS: abnormal joint alignment, proximal worse than distal; abnormal length tension relationship of all muscles affected by joint malalignment resulting in weakness proximal > distal</p> <p>NM: trunk muscle weakness and malalignment resulting in the development of inadequate postural control strategies and a constant conflict between breathing and postural needs</p> <p>CP: severe restrictive lung condition resulting in significant endurance impairments; impaired breathing mechanics, including paradoxical breathing (weak intercostal muscles); RR 32/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)</p> <p>INT: none (yet)</p> <p>IO: malnutrition; dehydration; no reflux; no connective tissue limitations around scars from previous surgeries or around her shoulders or pelvis</p>				
Functional limitations and impact on participation	<p>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.</p>				
Prioritize the current problems by categories	IO→	MS→	NM→	CP→	(INT)
Diagnosis	<p>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.</p>				
Prognosis	<p>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 rib cage 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, and to increase her potential to participate in normal childhood activities.</p>				
Pre and post surgical goals	<p>Pre surgery: Improve nutritional status, hydration, skeletal alignment of the trunk, and strength and control of the trunk musculature in order to improve Katie's breathing mechanics and cough effectiveness such that she can survive the scoliotic reduction surgery and the recovery phase.</p> <p>Post surgery: 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 of post surgical 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.</p>				
Interventions specific to Katie's short-term goal of surgical readiness	<p>MS: rib mobilization to maximize inspiratory lung volumes; other ROM of joints as needed</p> <p>NM: NM reeducation to increase intercostal activation for inspiratory lung volumes and chest wall stabilization; NM 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</p> <p>CP: 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</p> <p>INT: no short term interventions needed</p> <p>IO: 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</p>				

inspiration is difficult or impossible for these patients. This will markedly curtail the ability to produce an effective cough, to maintain bronchial hygiene, or to yell (Grimstone & Hodges, 2003).

APPLICATION OF THE SODA-POP CAN MODEL TO A CLINICAL EXAMPLE

Implicit in the Soda-Pop Can model of respiratory and postural control is the concept that impaired pressure regulation of the trunk may have resulted from an impairment in any body system that generates or uses this pressure, and thus all systems must be screened for their potential role in the motor dysfunction of breathing or postural control. Five such 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 demand of motor tasks (see Box 39-2). These ideas will now be applied to a clinical case.

Multisystem Evaluation, Examination, and Intervention

Case History

Katie is a 9-year-old female (Figure 39-14, A) with a congenital idiopathic scoliosis (infantile scoliosis) that required surgical stabilization of two upper thoracic vertebrae at three years of age. Several ribs fused on the concave side of the scoliosis after surgery and contributed to a continued progressive kyphoscoliosis as Katie matured. Spinal fusion from T1 to S1 was planned at age nine-and-a-half when the scoliosis reached 97 to 98 degrees despite conservative bracing from three years of age and close monitoring by the orthopedic surgeon.

The presurgical work up revealed that Katie's lungs were so severely restricted by her MS impairment that the pulmonologist was unsure she would survive the surgery. In other words, Katie's can of soda-pop was crushed, resulting in multiple body system dysfunctions even though the original impairment was in a single system: the MS system. Katie was referred to physical therapy to attempt to improve her restrictive lung condition in order to become a viable surgical candidate. Katie had not been referred to physical therapy before this time for any other type of intervention.

Impairment Categories. Using a multisystem examination and evaluation from the Soda-Pop Can model point of view, Katie's pathology was no longer noted as a single system motor dysfunction. The progression of her impairments, starting with the original insult to the MS system, is identified in (Table 39-2).

1. Katie's pathology started in the MS system, specifically the spinal skeletal system. Her skeletal support, the "aluminum can," had collapsed. Katie's muscle support matured around those deformities and did not develop optimal length tension relationships for maximal force

production (strength). Her muscle weakness was primarily in the trunk and proximal joints. Her distal extremity muscles showed less weakness. In particular, her chest intercostal muscles were so weak and underutilized that the negative pressure of inhalation caused her chest to be sucked inward (paradoxical breathing). She could not generate enough muscle force to counteract the internal negative pressures associated with normal inspiratory lung volumes. Fortunately, the paradoxical movement had not caused a pectus excavatum, but over time it was a real possibility. Her hips and shoulders matured around the malaligned spine, which resulted in additional joint dysfunction. Katie's mom reported that Katie was not a physically active girl, which was expected with her multiple joint limitations.

2. The MS weaknesses resulted in a secondary NM problem as her muscle recruitment and balance strategies developed around an atypical MS alignment that neither supported the symmetrical development of the body nor effectively supported the concurrent demands of pressure support in the trunk for respiratory and postural control. As a result, Katie's breathing pattern was atypical (paradoxical) and likely contributed to her reduced lung volumes.
3. Reduced lung volumes and limited physical activity led to significant endurance and mechanical impairments in the CP system. Katie's breathing mechanics were so compromised and her potential lung space so compressed that she developed a severe restrictive lung condition. No heart or vascular problems were noted per her physician at the time of her initial evaluation. Right-sided heart failure, cor pulmonale, however, which develops secondary to chronic pulmonary dysfunction, was a real risk for Katie as she matured.
4. The shape of the scoliosis severely impinged on the size of Katie's stomach, causing IO impairment that resulted in malnutrition and dehydration. Katie could only eat less than 200 calories per meal before feeling full. Fluids filled her up even quicker and made it hard for Katie to adequately hydrate herself and consume adequate calories. Fortunately Katie did not develop gastroesophageal reflux disease (GERD) from the abnormal pressures and malalignment.
5. Katie's INT system was functioning well and did not appear to cause any limitations in her motor performance. Her prior scars were well healed and not adhered to underlying surfaces. In spite of the severe spinal deformity, the connective tissue around her trunk and extremities was easily moved to allow the maximum mobility of the underlying skeletal structures. It would not have been a surprise, however, to have found connective tissue limitations preventing maximal MS movement.

Functional limitations. A functional assessment was also done to cross-check the evaluation from both perspectives: impairments and functional limitations. The functional findings confirmed the impairment findings: Katie had significant 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, underutilization of intercostals (especially on the left, concave side of her chest), and paradoxical breathing. Her respiratory rate (RR) was 32 breaths per minute with forced exhalations (normal RR is 10 to 20 breaths/min). With minor increased physical workload, such as walking fast, she responded by breathing faster, but not deeper. Not surprisingly, she had very poor physical endurance compared with her peers. Her forced vital capacity (FVC) was 33% of predicted value for her age and height, indicating a severe restrictive lung status.
2. Her cough sequence was normal, but the small lung volume impaired her expiratory force because there was simply not enough air to force out. Her peak expiratory flow rate (PEFR) was 59% of predicted value. Clinically, less than 60% of predicted PEFR has been associated with ineffective cough and increased risk of secondary pulmonary complications.
3. Katie's teachers complained that Katie fell asleep almost every afternoon in school and often complained of headaches. Given her severe restrictive lung condition and weak trunk muscles, I suspected nocturnal hypoventilation even though a sleep study three years prior showed no abnormalities. Hypoventilation can contribute to overall poor lung function during the day due to fatigue and could therefore account for some of her poor growth patterns. Her pulmonologist concurred and ordered a new sleep study. The chronic hypoventilation was confirmed in the sleep study.
4. Katie has always been quiet according to her mother. The question was whether she was naturally quiet or conserving energy. Her speech was three to five syllables per breath. Normal speech is eight to 10 syllables per breath (Deem & Miller, 2000). Her sustained phonation was 2.4 to 3.1 seconds. Normal sustained phonation is 10 seconds (Deem & Miller, 2000). Katie yelled when asked to do so, but her mom reported that she rarely ever yelled. Her lack of breath support could explain her quiet speech, short answers, and apparent reserved style. It was impossible to know whether Katie was quiet naturally or became quiet due to poor breath support over her entire lifetime.
5. Katie's stomach was compromised by the kyphoscoliosis, which made her feel full with less than 200 calories. Katie not only had poor weight gain, but as she got older and needed more calories for vertical growth, she actually started to lose weight and was not achieving the conservative vertical height goals that her orthopedic surgeon was hoping for before the spinal fusion.
6. Not surprisingly, Katie had marked endurance limitations in normal, age appropriate physical activities. Specifically, Katie fatigued when walking more than one-and-a-half lengths of the grammar school gym or riding her bike more than two-and-a-half blocks. Katie's body was focused on surviving, not thriving. Her weak muscles and poor breathing mechanics combined with inadequate caloric,

hydration, and oxygen fuel, meant that few reserves were left over from survival needs to support the thriving needs of gross motor activities such as running and jumping. Katie's body simply could not meet both the needs of breathing and higher level postural demands of normal childhood activities (Hodges et al, 2001; Gandevia et al, 2002). Katie preferred to engage in lower oxygen consuming activities such as playing the violin, reading, and playing quietly. The question was whether she really had a choice regarding her activities.

Priorities of Interventions. Understanding Katie's progression of impairments streamlined the screening process. Katie's pulmonary system was preventing her from having surgery. But pulmonary did not start out as her primary pathology. The questions this presented were how all five motor impairment categories contributed to her current pulmonary status and how to clinically prioritize the interventions to meet the short-term respiratory/surgical goals. In the short term, the evaluation directed me to prioritize the following interventions. Katie's long-term health and participation goals were developed after surgery.

1. Katie's poor nutritional status meant she had no caloric reserves to effectively engage in a conditioning program to strengthen her respiratory muscles in preparation for surgery. Likewise, her general state of dehydration would cause decreased mobility of pulmonary secretions, thus increasing her postsurgical risk of pneumonia and/or atelectasis. Thus, focusing on increasing Katie's nutritional and hydration needs was the first priority. Katie was instructed to eat at least six meals per day rather than three, and was given permission from her teachers to bring a water bottle to class. In school she was encouraged to drink at the start of every new subject. Katie's nutritional content was managed by her pediatrician.
2. Surgery was the recommended intervention to improve the long-term alignment of her spine and ribcage. In the short term, however, manual mobilization of her ribcage was a priority to gain any possible additional movement that could be used to increase lung volumes.
3. After Katie's ribcage mobility was increased and a position that gave her the best support for chest wall movement was identified (sitting), a NM program was initiated to improve the respiratory mechanics. The focus of the program was:
 - a. to increase the recruitment, strength, and function of the intercostal muscles as inspiratory muscles (for increased lung volume) and as chest wall stabilizers (to stop the paradoxical breathing), while decreasing the use of forced abdominal muscle exhalations, thus reducing her overall energy cost of breathing by using her trunk pressures more effectively,
 - b. to increase the power production of both inspiratory and expiratory muscles for increased lung volume and

increased cough effectiveness through use of peak flow meters and incentive spirometers for 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); ventilatory muscle training resistance was used instead of a traditional fitness training program such as treadmill training because Katie's weakness, malalignments, and painful joints would have prevented her from exercising long enough to be effective and may have actually caused other joint problems,
 - d. to improve Katie's ability to meet the conflicting needs of respiration and postural control necessary for functional endurance and motor performance by prescribing low level activities (walking) to start, increasing the distance (endurance), and providing instruction on how to use the new breathing pattern within a functional task to challenge her balance and respiratory needs simultaneously.
4. By addressing the contributions that all body systems had on the efficiency and effectiveness of Katie's breathing mechanics, her lung volumes, cough effectiveness, endurance impairments, and postural conflicts were targeted through multiple interventions to address her most pressing problem: pulmonary clearance for orthopedic surgery.
 5. Katie's INT system did not show any impairments and was not a significant contributor to her poor pulmonary status. However, after surgery, her dehydrated condition predisposed her to a potential skin breakdown and poor scar healing and therefore she had to be monitored for any emerging problems.

Diagnosis and Prognosis. Katie's MS pathology impaired the structural support of her trunk and respiratory mechanics. As a result of the innate interactions between the body systems, the MS restrictions resulted in dysfunction in numerous other systems. She was referred to physical therapy for one specific task: to improve her breathing mechanics such that she could undergo surgery to correct the initial pathology, the scoliosis. After the PT exam, the pulmonologist was contacted to discuss the findings and told that Katie's condition showed potential for improvement, but a minimum of four to six weeks was needed to achieve a true training effect that would hopefully sustain her through the long surgery. Surgery was put off for eight weeks to allow Katie the maximum benefit of the physical therapy intervention. For her long-term goals of improved health and participation in normal childhood related activities, it was obvious that improving her breathing mechanics was only one aspect that needed to be addressed. The other issues were to be addressed after surgery.

Outcomes. Katie and her mom understood the surgical risk and were very motivated to participate in an aggressive

physical therapy program that relied heavily on their home participation. Katie and her mom were instructed regarding the necessity of a home exercise program five days a week for four to six weeks in order to effect a true change in the status of the muscle strength and endurance. Katie did the exercises seven days per week instead. Specific pulmonary function test improvements are noted below along with their influence on her surgical status.

1. Katie's pulmonary function test (PFT) baseline for FVC was .45 L, which is 33% of predicted value (1.36 L), and her PEFr was 1.64 L/s, or 59% of predicted value.
 - a. Three weeks later, Katie's FVC improved to .57 L, or 42% of predicted value.
 - b. Five months later, FVC had increased to .63 L, or 45% of predicted value, where it held steady.
 - c. Three months after initiating her program, PEFr improved to 2.31 L/s, making it 81% of predicted value, which is within a normal range for effective cough.
 - d. Two years later, after a sleep study confirmed chronic hypoventilation and after successful initiation of bi-level positive airway pressure machine (Bi-PAP) nocturnal support, FVC improved to .71 L, but this value was now only 40% of predicted value for her age and height (1.78 L). The predicted values continue to climb with age in children, but Katie's lungs did not keep pace with expectations for a typically developing child. A predicted FVC value of 60% is often used as the clinical measurement of adequate lung volume necessary for normal pulmonary maneuvers such as coughing, sighing, sneezing, etc. At 40% she was still at long-term risk for secondary respiratory problems due to impaired lung volumes.
2. At four months, the orthopedic surgeon decided to put the surgery on hold because her scoliosis had reduced from 97 to 98 degrees to 90 to 92 degrees. He felt that her improved pulmonary status had a positive effect on her skeletal frame and that as long as she remained stable, it was worth holding off the surgery to give her every chance to grow and continue making respiratory gains before fusing her spine (see Figure 39-14, B).
 - a. Katie's surgery was held off for three-and-a-quarter years until Katie was 12 years old, allowing her to establish more vertical growth before the spinal fusion. The orthopedic surgeon expressed his surprise that she did not require the surgery before 10 years of age.
 - b. Katie continued to do her exercises three to four days a week for that entire time. She had no postoperative respiratory complications. Her scoliosis was markedly reduced but not eliminated (Figure 39-14, C). Katie may require additional surgeries later for her shoulders, hips, and fused ribs.

Numerous other aspects were involved in Katie's care, including an eventual gastric surgery for a gastrostomy-tube

placement to foster more effective nutritional gains, the initiation of growth hormones, the use of bi-PAP nocturnal support to reverse chronic hypoventilation and its effects on her physical endurance and growth, as well as a more comprehensive physical therapy program to focus on her overall growth and maturation. This report focused on the initial physical therapy intervention to illustrate how a multi-system assessment could be used to develop a differential diagnosis regarding her physical and pulmonary limitations. In this case Katie's scoliosis and subsequent muscle development made her incapable of generating, maintaining, and regulating adequate pressures in her trunk to support normal respiration, postural control, and IO function. The Soda-Pop Can model helped to explain why the impairment to her MS system had such far reaching implications on her health and the function of her other systems.

Quality of Life. In addition to medical improvement, Katie's mom reported that the respiratory and multisystem approach to Katie's physical therapy program "absolutely saved her life." Katie's confidence in her ability to influence her own destiny was noted at the second physical therapy visit, during which she saw the positive results of her diligent adherence to the home program: her impairment level improved in terms of PFTs and she achieved functional gains in her 12-minute walk test. Within six months of the initiation of the physical therapy program, Katie's paradoxical breathing was gone, 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 contributed to her increased physical activity. She started swimming lessons, joined recreational softball, and generally reported that she "likes this new feeling. It's easier to move and breathe." Her mom reported that Katie smiled more often.

Interpretation of the Clinical Relevance of this Case to Impaired Respiratory Mechanics. The CP system is one of many systems that creates and utilizes pressure support in the trunk for optimal performance, and it should not be assessed or treated in isolation from the potential influence that other body systems have on its performance. The body always functions as a whole unit with all the individual systems interacting and supporting one another; it does not act as a single system. In particular, postural control and the mechanical support for breathing are interdependent; yet breathing needs will always take precedence over postural needs. Therefore, mechanical support for breathing should be assessed and treated within the context of the mechanical support for postural control because both activities utilize the same space and the same muscles.

A diagnosis that stems from the MS system, such as for Katie, cannot be assessed from a single system perspective. As we saw with Katie, although the initial pathology stemmed from the MS system, her current problems were more pressing in the NM system (motor planning and strength), the CP system (severely impaired respiratory mechanics, inadequate respiratory endurance, and the risk for cardiac



FIGURE 39-15 Melissa, six years of age. Note the use of the TLSO 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 an ideal alignment of the proximal extremity joints (shoulders and hips) as well as the ideal head alignment for normal functions such as talking and eating.

impairments), and the IOs (persistent malnutrition and dehydration). If Katie had been treated for a single system impairment, this author does not believe that she would have had the significant clinical and functional successes that allowed her surgeon to delay her impending surgery more than three years.

BROADER APPLICATION

Pathologies stemming from any motor impairment category may result in impaired breathing mechanics and/or a conflict in postural control and breathing that interferes with motor performance. For example, a patient with a NM insult such as a spinal cord injury, cerebral palsy, CVA, or head injury will show impaired breathing mechanics and impaired postural control due to paralysis, weakness, or impaired motor planning or execution associated with those NM disorders. The therapist would need to assess such a patient from the neuro-motor perspective as well as that system's interaction with the MS, CP, INT, and IO systems before feeling confident that the major limiting impairment to motor performance and health had been correctly identified and prioritized for intervention. Dramatic changes in chest wall and trunk alignment can be achieved long term from a multisystem approach. See Melissa's changes from three to 12 years of age after a SCI birth trauma (compare Figures 39-15 and 39-16 with Figures 39-2, B and



FIGURE 39-16 Melissa, 12 years of age, after orthopedic surgery to reduce scoliosis. **A**, Note that the chest wall deformities that were so prevalent at age three are almost completely absent. The only noticeable skeletal restriction is the slight reduction in mid chest expansion noted around ribs six through eight, which looks like a high “waistline” just under her bra strap line in supine. The intercostal muscles, which were paralyzed, are the only support for the ribcage at that level. Melissa used her upper accessory muscles to support breathing and chest wall alignment of the upper chest, and the diaphragm for the lower ribcage. **B**, Melissa continues to wear an abdominal binder in upright postures, but it was removed for this picture.

39-8, C). Melissa’s chest wall and spinal deformities were almost completely reversed after years of interventions from a multidisciplinary team approach to her multisystem impairments (Massery, 1991). Melissa was not seen by a physical therapist or any physical medicine discipline until she was three-and-a-half years old. A few key long-term interventions and outcomes follow.

1. Melissa used an abdominal binder whenever she was upright to provide the abdominal pressures needed for IO support and improved breathing mechanics and lumbar stabilization. This will be a lifelong intervention.
2. In addition, Melissa needed a body jacket, or thoracic-lumbar-sacral orthosis (TLSO), with an abdominal cutout and abdominal binder. An abdominal binder alone was not enough 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 the eventual surgical correction easier, safer, and faster.
3. An aggressive NM 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 in how to use her breath support (ventilatory strategies) to improve her mobility skills, such as in rolling over and reaching.
4. A comprehensive airway clearance program was developed to minimize the family’s reliance on suctioning. Melissa and her family learned multiple manual assistive cough techniques that effectively expectorated the mucus. They reduced her suctioning from 24 to 36 times per day to one to three times per day. She had multiple pneumonias in her first three-and-a-half years of life, but none from age three to 12.
5. Melissa’s nutrition and hydration needs were attacked as a whole team to increase her caloric and hydration status. Her 12-year-old picture clearly shows that she learned to consume adequate calories for growth. (A gastrostomy tube was not used as it had not yet been invented when Melissa was a young girl.)
6. Melissa was initiated on nocturnal positive pressure ventilation support at approximately six years of age due to nocturnal hypoventilation and the conflict between the use of calories for growth or breathing. The positive pressure support obviously relieved her work of breathing and gave her muscles a daily rest, but it also provided pressure support to reverse the pectus forces.

The same concept can be applied for any other impairment category. For example, in Katie’s case, if her INT system showed connective tissue restrictions secondary to the kyphoscoliosis, then her INT system would have been the primary limiting factor to improving her pulmonary status rather than her NM and IO systems. In other words, if her

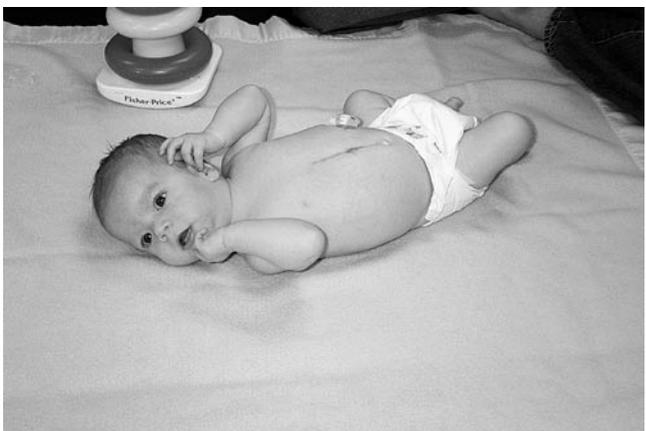


FIGURE 39-17 Jonathan, six months of age. His severe gastroesophageal reflux required surgical support (gastrostomy tube and Nissen fundoplication procedures) at five months of age. His mother reports that his favorite posture when in supine is extreme trunk extension and right head rotation. This may have developed as a compensatory strategy against the noxious stimulus from reflux and a possible upper airway obstruction that was yet undiagnosed.

ribcage was capable of being mobilized but the overlying skin did not allow movement into the new range due to connective tissue shortening, then Katie would not have been capable of learning to use new breathing strategies to increase her lung volumes. This is noted dramatically in patients who have connective tissue disorders such as scleroderma or severe burns: the skin no longer has the mobility to allow the underlying muscles to move the chest wall adequately to inhale lung volumes necessary to meet the oxygen needs of motor tasks. How restrictive their breathing is depends on the severity of the condition and damage to the INT structures.

Conditions related to the IO system may have a more subtle influence on postural control and breathing. Infants with severe gastroesophageal reflux may assume a posture of trunk extension and right head rotation in a supine position (Sandifer's syndrome) (Werlin et al, 1980; Senocak et al, 1993; Gorrotxategi et al, 1995; de Ybarrondo & Mazur, 2000; Demir et al, 2001) (Figure 39-17). This posturing may be mistaken initially for a true NM 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 erroneously treat the excessive extension tone and asymmetry of the trunk rather than the underlying cause of the motor behavior, which stems from the IO system. If untreated, these infants tend to develop more trunk extension and upper chest breathing strategies to avoid exacerbating the reflux, which occurs when the diaphragm descends onto the irritable stomach, and to avoid

increasing intraabdominal pressure, which may also contribute to reflux. Over time, that child may develop impairments in all motor systems, and this could affect the child's overall health and participation potential. For example, children with cystic fibrosis are tipped downward for postural drainage to improve lung function, but it is now known that the treatment predisposes the children to reflux and a worsening of their pulmonary condition (Button et al, 2003; Button et al, 2004). The outline below describes how all motor systems could be affected by a pathology starting in the IO system.

1. IO system: The pathology started here.
2. NM system: Inadequate motor control of trunk flexors, necessary for balance, forced expiratory maneuvers, and lumbar stabilization, may develop. An IO pathology potentially predisposes the child to later 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. MS system: A sequelae of connected events is possible, such as (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 never 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. CP system: Poorer overall endurance may result if the child develops an upper chest 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/or shoulder dysfunction because the conflict between the respiratory recruitment of the upper accessory muscles and the dual role these same muscles play in upper quadrant movement may cause over-utilization and later complaints of pain, fatigue, headaches, etc.
5. INT system: This is generally not a major problem area, but the potential exists for inadequate connective tissue mobility that may restrict movement into flexion patterns of the trunk, shoulder, or hip.

The clinical examples are endless. Impaired breathing mechanics do not occur only because of a direct impairment of the lungs, airways, or chest wall muscles. Impaired breathing mechanics can occur from insults to any system that influences motor performance. The CP system should be seen as an integral part of all motor assessments in order to determine whether the mechanics of breathing are working for or against the patient's overall motor performance. In other words, breathing mechanics may be the cause or the consequence of motor dysfunction and a thorough multi-system evaluation should help the clinician determine the difference.

SUMMARY

In this chapter, the role of the respiratory mechanics as they relate to other body systems has been explored. Gravity was presented as a significant influence on both the potential movement of the chest and the normal development of the chest and trunk. The relationship of the dual role of the trunk in support of both respiration and postural control was introduced in the form of the Soda-Pop Can Model. These concepts were then applied to clinical cases from multiple motor impairment categories to illustrate how trunk control, breathing, and internal functions are dependent on the ability of the body to generate, maintain, and regulate pressure in the thoracic and abdominal chambers; the control of which extends from the vocal folds down to the pelvic floor. Using clinical examples, all five motor impairment categories—MS, NM, CP, INT, and IO systems—were screened for their potential role in motor performance and breathing mechanics because each system influences the performance of the other. This information was then used to design a treatment plan that effectively targeted the primary impairments and successfully achieved a desired motor outcome that involved the trunk and breathing.

Review Questions

1. Explain the role of gravity in normal chest wall development of infants.
2. Explain how the pressure in the thorax and abdomen helps to 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. Take one of your patients and apply the concept of a multisystem evaluation, examination, and intervention planning as was demonstrated in this chapter.

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