

Foundations of Speech and Hearing

Anatomy and Physiology

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Preface

Almost a decade ago the two of us and Tom Hixon entered into conversations with Sadanand Singh, President of Plural Publishing at the time, to write a speech science textbook that would combine solid, detailed anatomical material on the speech apparatus with information on contemporary speech physiology and speech acoustics and perception. To our knowledge this was the first attempt to present an in-depth textbook treatment of anatomy, physiology, acoustics, and perception. The aim of the presentation level was somewhere between the stripped-down, simplistic presentations of some texts available at that time, versus the extreme detail presented in at least one popular text that relied on a preponderance of anatomical information, with very limited information on speech physiology and speech acoustics. The text that resulted was *Preclinical Speech Science: Anatomy, Physiology, Acoustics and Perception*, published in 2008. Judging from sales and reviews, the text was a success.

In 2012 we initiated work on a second edition of *Preclinical*. We sought feedback on what instructors and students liked and did not like about the first edition, and a recurring theme in the feedback was the absence (and desirability) of a chapter on the neural basis of speech, hearing, and language. We prepared a chapter to address this material, made changes to all the original chapters, and the second edition of *Preclinical* was published in 2014. At the time of this writing, a third edition of *Preclinical* is under development in which we will update, refine, and enhance the existing text as well as add materials to better meet the needs of students in communication sciences and disorders programs.

When seeking feedback on the second edition of *Preclinical*, we heard many requests for a chapter on the auditory system, something that would serve the needs of undergraduate courses that combine speech and hearing anatomy and physiology. The original plan for *Preclinical* was to support an intensive graduate-level course in speech anatomy, physiology, and acoustics for students working toward their clinical master's degree in speech-language pathology. At the same time, we came to the conclusion that the text could be modified to fit more squarely with the aims of undergraduate curricula in communication sciences and disorders. The book you hold in your hand, *Foundations of Speech and Hearing: Anatomy and Physiology*, is that modification. The present text includes the best aspects of *Preclinical*, although reduced in scope and detail. It also contains a new chapter on auditory anatomy and physiology. We feel it is the right fit for an undergraduate course on speech and hearing anatomy and physiology—it is neither oversimplified nor excessively detailed, and the presentation is always guided by our concept of the information required for the next step in the education of speech-language pathologists and audiologists. Importantly, the high-quality images of *Preclinical*, so central to the quality of that text, have been retained and enhanced in the current *Foundations* text.

Although the current text lists two authors, a significant portion of the material was originally conceptualized and written by Tom Hixon (1940-2009). If this current text has any merit or even excellence, it is in no small part due to Tom's extraordinary vision and effort in making the first edition of *Preclinical* a reality.

Enjoy the wonders of the anatomy and physiology of the speech and hearing apparatus.

Acknowledgments

Many of the people we acknowledge for contributions to this text are the same people we thanked for the first and second editions of *Preclinical Speech Science*. Even if their efforts are historical, their influence is reflected in the current textbook. In addition, Anna Ohlinger and Bianca Schroeder at UW-Madison made valuable editing and proof-reading contributions to the new material in the current text.

Once again, to Tom and Sadanand, still the roots of this branching tree.

Introduction

The study of anatomy and physiology of speech and hearing is pleasurable to some students and painful to others. We hope that this book will bring at least some pleasure to all readers, even those who think they are not interested in the “dry” sciences. This book is written to be thorough and accurate. It is also written with clinical endpoints in mind; thus, only those topics that are ultimately important to understanding, evaluating, and managing clients with speech, hearing, and swallowing disorders are covered.

One outgrowth of this clinical mindset is that this book differs from others of its genre in certain of its conceptualizations. Some examples are provided here.

The respiratory (breathing) subdivision of the speech mechanism is covered in all speech-related anatomy and physiology textbooks, as it is in this one. All such books provide illustrations of the different structures, list the muscles and their functions, and describe the general process of breathing; this book does as well. What sets this book apart is the cogent and relatively simple description of how this extremely complex system operates for various activities through focus on the functional components of the breathing apparatus, especially the chest wall (rib cage wall, diaphragm, and abdominal wall). This firmly grounded and clinically driven approach to presenting material on the breathing apparatus (see Chapter 2) is rooted in the work of Thomas J. Hixon who generated the seminal research in this area and the fact that the authors of this book, both of whom were mentored by Dr. Hixon, have also contributed to our understanding of speech breathing.

Most textbooks divide the speech mechanism into three or four subsystems. The first two, respiratory (breathing) and laryngeal, are also used in this book. Where this book diverges from the others is in the treatment of the region above the larynx. Some textbooks present this region as a single subdivision of the speech mechanism, often called *articulatory* and encompassing the pharyngeal, oral, and nasal cavities and associated structures. Other textbooks present this region as two subdivisions, using terms such as *articulatory* (meaning the oral region) and *resonatory* (meaning the velopharyngeal and nasal regions). There are problems with using these terms in this context. One is that not all the articulators are in the *articulatory* subdivision; the larynx also acts as an articulator (see Chapters 3 and 5). Another problem is that the resonators are not exclusively found in the velopharyngeal and nasal regions; the lower pharynx and the oral cavities also serve as acoustic resonators. And yet another problem is that these regions are not used exclusively for articulating or resonating but also serve other functions, such as swallowing. In this book, the regions above the larynx are presented as two subdivisions, one called velopharyngeal-nasal and the other called pharyngeal-oral. These terms may seem cumbersome, but they are precise and convey a clear conceptualization of these regions and their functions. The velopharyngeal-nasal apparatus includes both the velopharynx and the nasal airways and associated structures. As readers will understand after reading Chapter 4, inclusion of the nasal portion of the apparatus is critical to understanding the aeromechanic and acoustic functions of this part of the

speech mechanism. The pharyngeal-oral apparatus includes the middle and lower pharynx and the oral cavity and associated structures. The inclusion of the pharyngeal part of the apparatus in this subdivision reflects the fact that during speech production, this part of the pharynx acts as an articulator along with its oral counterparts.

There are other features that set this book apart. To begin, the illustrations, nearly all of which have been created by artist Maury Aaseng, are masterfully crafted and support the text by focusing on the salient structures. Also, a full chapter is devoted to swallowing, an area of study that has assumed enormous clinical importance over the past few decades. And, finally, coverage of neural control is distributed throughout all the chapters, including an in-depth treatment of the topic in Chapter 7.

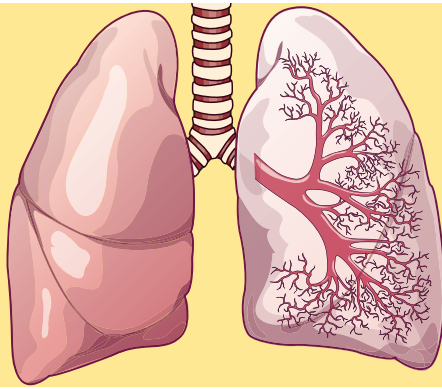
This book draws heavily from our book titled *Preclinical Speech Science: Anatomy, Physiology, Acoustics, Perception* (Hixon, Weismer, & Hoit, 2014). In fact, much of this book is either directly taken from the *Preclinical*

book or is a modified version of it. Modifications comprise some simplifications and clarifications to help the readers of *Foundations* who are less familiar with the topics covered. The exception is a brand new chapter on auditory anatomy and physiology that has been added to this book. In the spirit of the other chapters, the material included in this new chapter organizes the information as a foundation for clinical aspects of auditory function.

It should be noted that this “spin-off” book has been produced without express agreement of Thomas J. Hixon (1940–2009). We hope that he would have condoned our efforts to make this material more accessible to students at all levels of training.

REFERENCE

- Hixon, T. J., Weismer, G., & Hoit, J. D. (2014). *Preclinical speech science: Anatomy, physiology, acoustics, perception*. San Diego, CA: Plural.



2

Breathing and Speech Production

INTRODUCTION

It is estimated that 15% of individuals with speech disorders have problems that are caused, at least in part, by abnormalities of speech breathing. A speech breathing disorder may have functional and/or organic origins and may present as a problem of breathing movement, gas exchange, breathing comfort, or any combination of these (Hixon & Hoit, 2005). To recognize, evaluate, and manage speech breathing disorders, it is necessary to understand normal speech breathing and its anatomical and physiological underpinnings.

This chapter begins by considering the structures and general functions of the breathing apparatus and then turns to consideration of breathing for normal speech production. This is followed by a discussion of selected variables that are known to influence speech breathing.

FUNDAMENTALS OF BREATHING

The breathing apparatus is a mechanical air pump. This section considers the nature of this pump and how it functions. Topics discussed include the anatomical bases of breathing, forces and movements of breathing, adjustments of the breathing apparatus, output

Coming to Terms

Terms can enlighten you or get you into verbal quagmires. Respiratory physiologists have gone out of their way to be precise in their use of terms. They've even held conventions to iron out their differences in language. It's a good idea to take a little extra time and care when reading the early sections of this chapter. Let the lexicon of the respiratory physiologist take firm root. Don't be tempted to skip over parts just because the words in the headings look familiar to you. You may be surprised to find that a term you thought you understood actually has an entirely different meaning to a respiratory physiologist.

variables of breathing, neural control of breathing, and ventilation and gas exchange during tidal breathing. For the purposes of this chapter, the breathing apparatus is considered to include the pulmonary apparatus and chest wall (both defined below). Structures of the laryngeal apparatus, velopharyngeal-nasal apparatus, and pharyngeal-oral apparatus are covered in other chapters.

Anatomical Bases of Breathing

The breathing apparatus is located within the torso (body trunk). A skeleton of bone and cartilage forms a superstructure for the torso. This superstructure is depicted in Figure 2-1.

Skeletal Superstructure

At the back of the torso, 34 irregularly shaped vertebrae (bones) form the vertebral column or backbone. The uppermost 7 of these vertebrae are termed cervical (neck), the next lower 12 are called thoracic (chest), and the next three lower groups of 5 each are referred to as lumbar, sacral, and coccygeal (collectively, abdominal). The vertebral column constitutes a back centerpost for the torso.

The ribs comprise most of the upper skeletal superstructure. They are 12 flat, arch-shaped bones on each side of the body. The ribs slope downward from back to front along the sides of the torso, forming the rib cage and giving roundness to the superstructure. At the front, most of the ribs attach to bars of costal (rib) cartilage, which, in turn, attach to the sternum or breastbone. The sternum serves as a front centerpost for the rib cage. The typical rib cage includes upper pairs of ribs attached to the sternum by their own costal cartilages, lower pairs that share cartilages, and the lowest two pairs that float without front attachments.

The rest of the upper skeletal superstructure is formed by the pectoral girdle (shoulder girdle). This structure is near the top of the rib cage. The front of the pectoral girdle is formed by the two clavicles (collar bones), each of which is a strut extending from the ster-

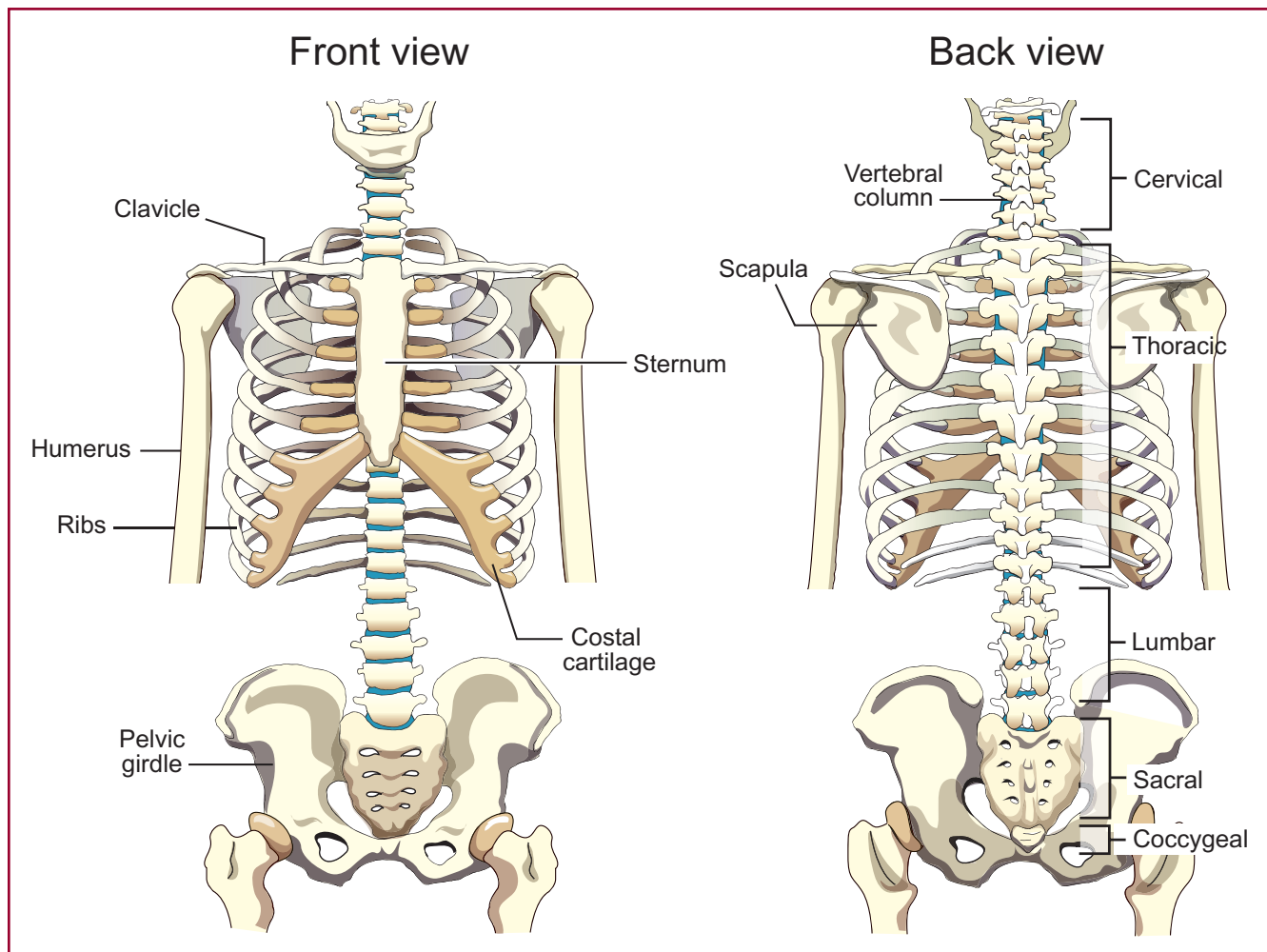


FIGURE 2-1. Skeletal superstructure of the torso consisting of the clavicles, ribs, sternum, pelvic girdle, scapulae, and vertebral column.

num over the first rib toward the side and back of the rib cage. At the back, the clavicles attach to two triangularly shaped plates, the scapulae (shoulder blades). The scapulae cover most of the upper back portion of the rib cage.

Two large, irregularly shaped coxal (hip) bones are located in the lower skeletal superstructure. These two bones, together with the sacral and coccygeal vertebrae, form the pelvic girdle (bony pelvis). The pelvic girdle comprises the base, lower back, and sides of the lower skeletal superstructure.

Breathing Apparatus and Its Subdivisions

The breathing apparatus (breathing pump) and its subdivisions are depicted in Figure 2–2. The torso, which houses the apparatus, consists of upper and lower cavities that are partitioned by the diaphragm. The upper cavity is called the thorax (or colloquially the chest) and is almost totally filled with the heart and lungs; the lower cavity, the abdomen or belly, contains much of the digestive system and other organs and glands. The structures of the breathing apparatus form two major

subdivisions, the pulmonary apparatus and chest wall. These subdivisions are concentrically arranged, with the pulmonary apparatus being surrounded by the chest wall.

Pulmonary Apparatus

The pulmonary apparatus is the air containing, air conducting, and gas exchanging part of the breathing apparatus. Figure 2–3 portrays some of its salient features. The pulmonary apparatus provides oxygen to the cells of the body and removes carbon dioxide from them. The apparatus can itself be subdivided into two components, the pulmonary airways and lungs.

Pulmonary Airways. The pulmonary airways constitute a complex network of flexible tubes through which air can be moved to and from the lungs and between different parts of the lungs. These tubes are arranged like the branches of an inverted deciduous tree. The network, in fact, is commonly referred to as the pulmonary tree.

The trunk of the pulmonary tree (the top part) is the trachea or windpipe. The trachea is a tube attached

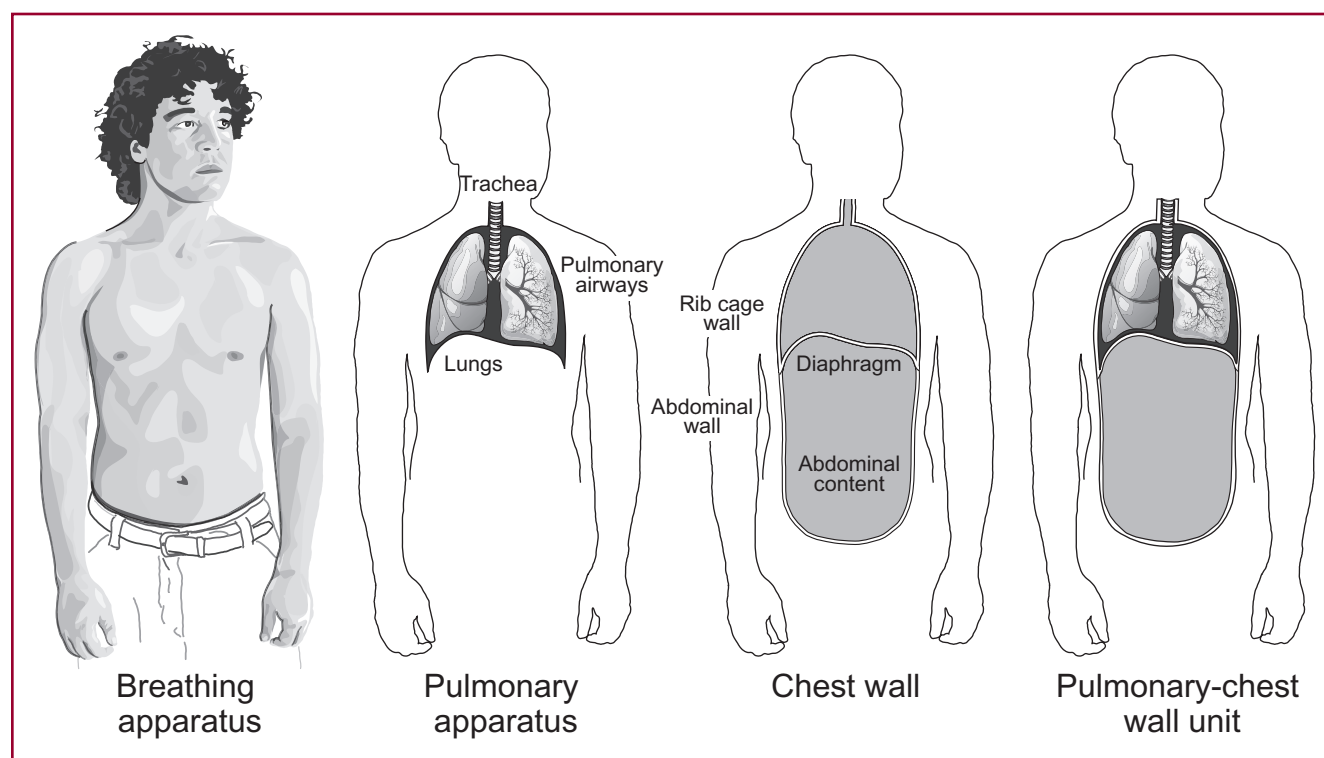


FIGURE 2-2. Breathing apparatus and its subdivisions: the pulmonary apparatus (lungs and airways) and the chest wall (rib cage wall, diaphragm, abdominal wall, and abdominal content). From *Evaluation and management of speech breathing disorders: Principles and methods* (p. 13), by T. Hixon and J. Hoit, 2005, Tucson, AZ: Redington Brown. Copyright 2005 by Thomas J. Hixon and Jeannette D. Hoit. Modified and reproduced with permission.

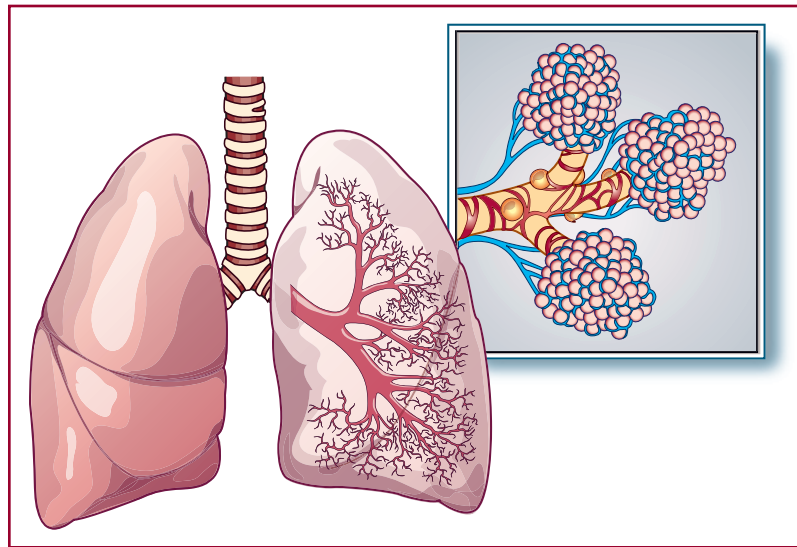


FIGURE 2-3. The pulmonary apparatus consisting of the airways (trachea, main-stem bronchi, lobar bronchi, segmental bronchi, subsegmental bronchi, small bronchi, terminal bronchi, bronchioles, terminal bronchioles, respiratory bronchioles, alveolar ducts, alveolar sacs, and alveoli) and lungs (spongy structures that surround the pulmonary airways).

to the bottom of the larynx (voice box). It runs down through the neck into the torso. The trachea is composed of a series of C-shaped cartilages whose open ends face toward the back where the structure is completed by a flexible wall shared with the esophagus (a muscular tube leading to the stomach). At its lower end, the trachea divides into two smaller tubes, one running to the left lung and one running to the right lung. These two tubes, called the main-stem bronchi, branch into what are called lobar bronchi, tubes that run to the five lobes of the lungs (two on the left and three on the right). The five lobar bronchi each branch and their offspring also each branch, and so on, through more than 20 generations. Each successive branching leads to smaller and less rigid structures. These include, in succession, segmental bronchi, subsegmental bronchi, small bronchi, terminal bronchi, bronchioles, terminal bronchioles, respiratory bronchioles, alveolar ducts, alveolar sacs, and alveoli. The last, the alveoli, are extremely small cul-de-sacs filled with air. They number more than 300 million and are the sites where oxygen and carbon dioxide are exchanged.

Lungs. The lungs are the organs of breathing. They are a pair of porous and spongy cone-shaped structures. Each lung contains many resilient elastic fibers and behaves like a stretchable bag. The outer surfaces of the lungs are covered with a thin airtight membrane, the visceral pleura. A similar membrane, the parietal

pleura, covers the inner surface of the chest wall where it contacts the lungs. Together these two membranes form a double-walled sac that encases the lungs. Both walls of this sac are covered with a thin layer of liquid that lubricates them and enables them to move easily upon one another. The same layer of liquid links the visceral and parietal membranes together, in the way that a film of water holds two glass plates together. This is called *pleural linkage*. Thus, the lungs and chest wall tend to move as a unit; where one goes the other follows.

Chest Wall

The chest wall encases the pulmonary apparatus. There are four parts to the chest wall: the rib cage wall, diaphragm, abdominal wall, and abdominal content.

Rib Cage Wall. The rib cage wall surrounds the lungs and is shaped like a barrel. The rib cage superstructure includes the thoracic segments of the vertebral column, the ribs, the costal cartilages, the sternum, and the pectoral girdle. The rest of the rib cage wall is formed by muscular and nonmuscular tissues that fill the spaces between the ribs and cover their inner and outer surfaces.

Diaphragm. The diaphragm forms the floor of the thorax and the roof of the abdomen. The diaphragm separates the thorax and abdomen, and thus, gets its name:

diaphragm, meaning *the fence between*. The diaphragm is dome-shaped and looks like an inverted bowl. The left side of the diaphragm is positioned slightly lower than the right (to accommodate the heart above and the liver below). At its center, the diaphragm consists of a tough sheet of inelastic tissue, the central tendon. The rest of the structure is formed by a sheet of muscle that rises as a broad rim from all around the lower portion of the inside of the rib cage and extends upward to the edges of the central tendon.

Ribbit, Ribbit

Ever watch a frog breathe? Did you notice how its cheeks moved? Frogs don't have a diaphragm to pull air into their lungs. They push the air in, using their mouths like pistons. Frogs are positive pressure breathers. People are negative pressure breathers. A frog doesn't have the ability to emulate us (except, perhaps, Kermit) if its positive pressure pump fails. But we have the ability to emulate the frog if our negative pressure pump fails by doing what is called glosopharyngeal breathing. And what would you suppose is the common name for such breathing? Well, it's *frog breathing*. In frog breathing, the tongue and throat are used to pump air into the lungs. Air is gulped in small portions (mouthfuls), each held in place by closing the larynx as a one-way valve. Frog breathing isn't difficult to learn and once mastered can be used to fill the lungs in a stepwise fashion all the way to the top.

Abdominal Wall. The abdominal wall provides a casing for the lower half of the torso. This casing is shaped like an oblong tube and runs all the way around the torso. The lower part of the skeletal superstructure of the torso forms the framework around which the abdominal wall is built. This includes a back centerpost of 15 vertebrae (lumbar, sacral, and coccygeal) that extends from near the bottom of the rib cage to the tailbone and pelvic girdle. Much of the abdominal wall consists of two broad sheets of connective tissue and several large muscles. The two sheets of connective tissue cover the front and back of the abdominal wall and are called the abdominal aponeurosis and lumbodorsal fascia, respectively. Muscles are located all around the abdominal wall—front, back, and flanks—and combine with the abdominal aponeurosis, lumbodorsal fascia, vertebral column, and pelvic girdle to form its encircling casing.

Abdominal Content. The abdominal content is everything in the abdominal cavity. This includes a wide array of structures, such as the stomach, intestines, and various other internal structures. This content is close to unit density (the density of water) and constitutes a relatively homogeneous mass. This mass is suspended from above by a suction force at the undersurface of the diaphragm and is held in place circumferentially and at its base by the casing of the abdominal wall. Together, the abdominal cavity and the abdominal content are the mechanical equivalent of an elastic bag filled with water.

Pulmonary Apparatus-Chest Wall Unit

The pulmonary apparatus and chest wall form a single functional unit that derives from the linkage effected by the pleural membranes. As illustrated in Figure 2-4, the

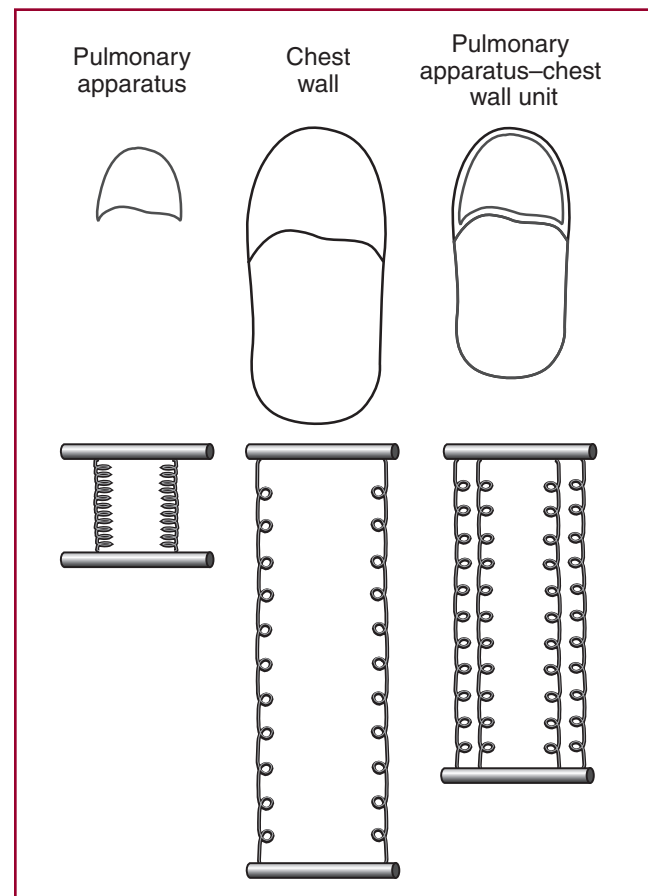


FIGURE 2-4. Resting positions of the pulmonary apparatus, chest wall, and pulmonary apparatus-chest wall unit (breathing apparatus). Note that the resting position (size) of the pulmonary apparatus is larger and the resting position (size) of the chest wall is smaller when the two parts are linked than when they are separated.

resting positions of the pulmonary apparatus and chest wall when linked are different from their individual resting positions when the two are separated. When the pulmonary apparatus is removed from the chest wall, its resting position is a collapsed state in which it contains very little air. This is represented as a collapsed spring in the figure (lower left). In contrast, the resting position of the chest wall, with the pulmonary apparatus removed, is a more expanded state, represented as a stretched spring in the figure (lower middle). With the pulmonary apparatus and chest wall held together by pleural linkage, the breathing apparatus assumes a resting position between these two positions such that the pulmonary apparatus is somewhat expanded and the chest wall is somewhat compressed. This resting position of the linked pulmonary apparatus-chest wall unit is a mechanically neutral or balanced state in which the force of the pulmonary apparatus to collapse is opposed by an equal and opposite force of the chest wall to expand. The linked pulmonary apparatus-chest wall unit (breathing apparatus) is represented as a combined spring in the figure (lower right).

Forces and Movements of Breathing

Forces applied to and by different parts of the breathing apparatus result in movements. Such forces and movements constitute breathing at the mechanical level.

Forces of Breathing

Passive and active forces operate on the breathing apparatus. Passive force is inherent and always present. Active force, in contrast, is applied willfully and in accordance with ability.

Passive Force

The passive force of breathing comes from: (a) the natural recoil of muscles, cartilages, ligaments, and lung tissue, (b) the surface tension of alveoli, and (c) the pull of gravity. These forces cause the breathing apparatus to behave like a coil spring, which, when stretched or compressed, tends to recoil toward its resting length.

The sign (inspiratory or expiratory) and magnitude of passive force depends on the amount of air in the breathing apparatus. When the apparatus contains more air than it does at rest, it recoils toward a smaller size (expires), like the release of a stretched spring. The more air in the apparatus, the greater the recoil force to expire. In contrast, when the apparatus contains less air than it does at rest, it recoils toward a larger size (inspires), like the release of a compressed spring. The less air in the apparatus, the greater the recoil force to

inspire. Thus, like a coil spring, the more the breathing apparatus is deformed from its resting size, whether in the inspiratory (stretched) or expiratory (compressed) direction, the greater the passive recoil force it generates.

Active Force

The active force of breathing comes from the actions of muscles of the chest wall. The sign (inspiratory or expiratory) and magnitude of this force depend on which muscles are active and in what combinations. Active force also depends on the amount of air in the breathing apparatus. The more air in the apparatus, the greater the active force that can be generated to expire, and the less air in the apparatus, the greater the active force that can be generated to inspire.

The roles of individual muscles in generating active force are described below for the rib cage wall, diaphragm, and abdominal wall. These descriptions assume that only the muscle under consideration is active and that it is shortening during contraction. It should be noted, however, that several factors might influence the contribution of an individual muscle, including the actions of other muscles, the mechanical status of different parts of the chest wall, and the breathing activity being performed.

Muscles of the Rib Cage Wall. The muscles of the rib cage wall are defined to include muscles of the neck and rib cage. These muscles are depicted in different views in Figure 2–5.

Rib Torque

Sounds like leftovers. Actually, it refers to rotational stress produced when one end of a rib is twisted out of line with the other. Some have suggested that when the ribs are elevated during resting tidal inspiration, they're twisted outward (placed under positive torque) and store energy, which is then supposedly released during expiration. Not so. The ribs are actually twisted inward (are under negative torque) at the resting tidal end-expiratory level. The lungs are pulling inward on the rib cage wall at that level. The ribs untwist during resting tidal inspiration, but do not reach neutral (zero torque) in the upright body position until the 60% VC (percent vital capacity) level is attained. Resting tidal inspiration involves only about a 10% VC increase, from say, 40% to 50% VC. Thus, rib torque actually opposes resting tidal expiration rather than assists it. The only thing leftover about rib torque in this context is the folklore.

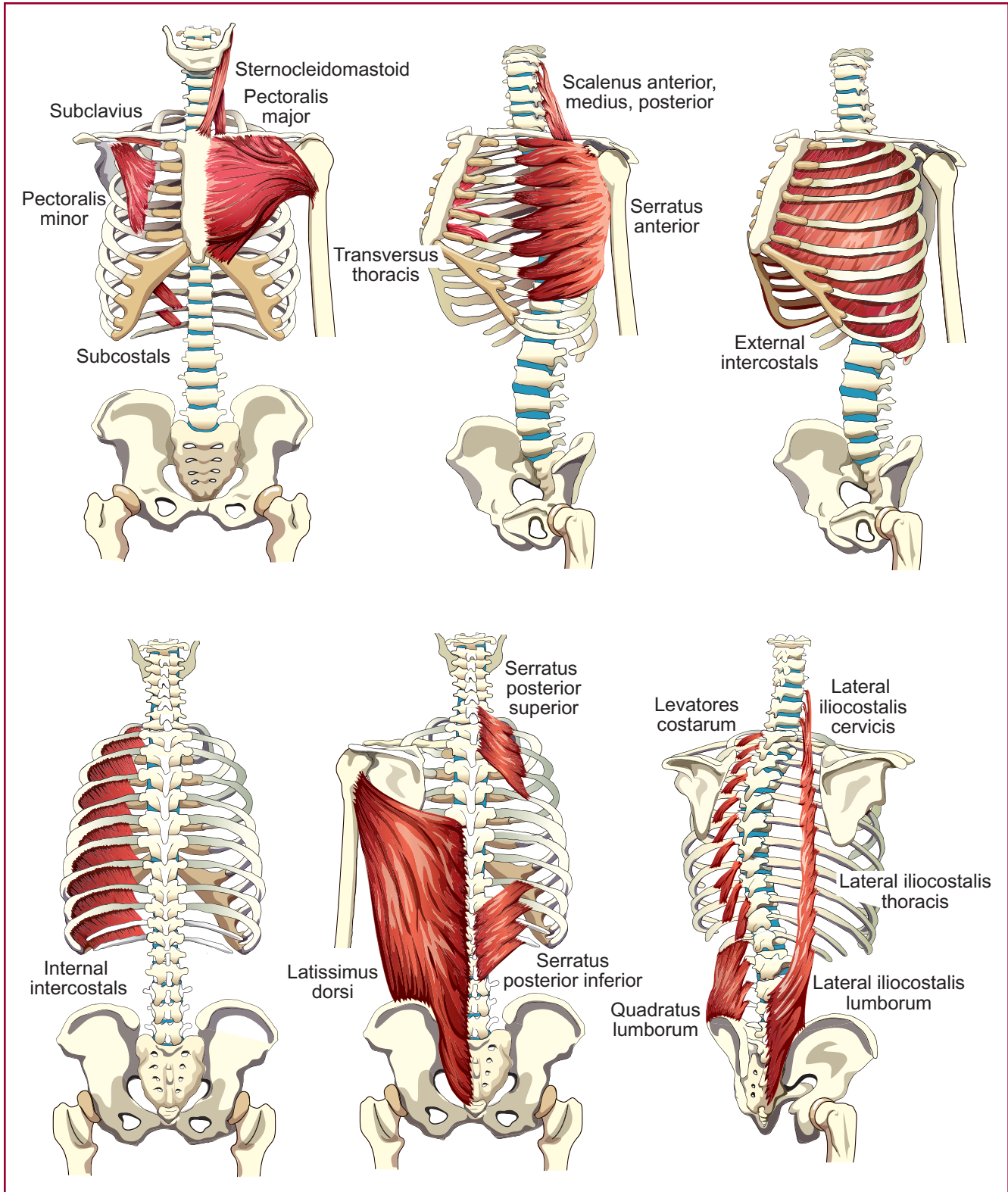


FIGURE 2-5. Muscles of the rib cage wall. From *Evaluation and management of speech breathing disorders: Principles and methods* (pp. 19–20), by T. Hixon and J. Hoit, 2005, Tucson, AZ: Redington Brown. Copyright 2005 by Thomas J. Hixon and Jeannette D. Hoit. Modified and reproduced with permission.