Adding Intelligence to a Textbook for Human Anatomy with a Causal Concept Map Based ITS

Ben Kluga¹, Manohar Sai Jasti¹, Virginia Naples², and Reva Freedman¹

¹ Department of Computer Science, Northern Illinois University benkluga@gmail.com, {mjasti, rfreedman}@niu.edu ² Department of Biological Sciences, Northern Illinois University vlnaples@niu.edu

Abstract. The need for intelligent textbooks is keenly felt in the field of anatomy where students find the breadth and depth of the material challenging. To properly handle the complexity of the subject, a hierarchical causal concept map based ITS platform was developed. This system features a general purpose architecture which takes as input a specific instance of a concept map, allowing authors to build multiple ITSs for different topics. This system improves on its predecessors by introducing additional components to the concept map as well as multiple types of relationships. These improvements allow students the opportunity to interact with the topics at a deeper level than required by traditional textbooks.

Keywords: intelligent tutoring systems, biology education, teaching anatomy and physiology

1 Introduction

Human anatomy is required for both undergraduate and graduate students in health related disciplines. This subject is a significant part of the early curricular foundation in these fields. Anatomy is complex, rich in both fact and concept, and emphasizes integration of many levels of understanding. Undergraduates studying anatomy at Northern Illinois University include majors in the health related professions, from pre-physical therapy, premed and predental to nursing and med tech. Other students taking anatomy include physical education and biological sciences majors. Graduate programs requiring anatomical study include physical therapy and graduate students in biological sciences. Other universities with medical and dental schools also teach this subject.

The Northern Illinois University anatomy curriculum is divided into lower level undergraduate courses in functional human anatomy and anatomy and physiology (juniorsenior 300 level). Upper level courses are for graduate biology students and physical therapy majors (400-500 level). This is a typical distribution of course types and levels across universities. Regardless of major or course level, students find anatomic topics difficult because they require simultaneous understanding of many disparate bodies of fact. The demand for high informational integration from many subfields of biology is the crux of the difficulty that students face in learning human anatomy.

There are two traditional ways to teach anatomy. The first is the systemic approach, where the components of each anatomic system are described and discussed independently. While this approach provides an understanding of all aspects of each anatomic unit, it neglects the interrelatedness that allows all body systems to function together. The second method is the regional approach, in which all anatomic systems in each region are studied simultaneously. This permits understanding of the interrelation-ships among different systems, but fails to demonstrate how these components relate to their native system in all other body regions.

Another problematic aspect in anatomy teaching is the requirement to increase the depth of understanding students achieve of each anatomic system. For example, one level at which the muscular system must be understood is identification of all muscles that move body parts. However, a deeper level requires assimilation of the details of muscle structure as a tissue, i.e., the ability to differentiate skeletal (= voluntary) and autonomic (= involuntary) muscles. An even more detailed level is the mechanism by which muscles move (the sliding filament theory of muscular contraction). The role of muscle as a body tissue can be understood at the cellular, and molecular and biochemical, levels as well.

All of these concerns relate to structure as well as function, which is also often described as physiology, and to understanding the muscular system in the human body. Muscles move bones, but this fact reveals little of the story until an understanding of how each muscle or muscle group moves the bone or bones to which it or they attach or attaches. Assembling all of these levels of knowledge nevertheless falls short of a full understanding of this system, because functional interpretations are required to know the results of the movement of each muscle or muscle group. A specific example of the complexities relating structure to function is exemplified by the diaphragm. It is the main muscle that controls intrathoracic volume, but increasing respiratory demand stimulates sequential contraction of additional muscles. These changes are mediated by the nervous system, but are also correlated with body movements determined by gait.

Anatomy teaching methods can explore these different depths and breadths of study, but the high degree of integration of understanding of structure and function at all levels of detail simultaneously requires a clear plan. Many attempts have been made to provide facts and concepts integrated with the functions of anatomical systems, but because of the complexity of these interrelationships, anatomic study would benefit from a new approach, using Artificial Intelligence (AI). The purpose of this research project is to provide a new model for the teaching of anatomical information in an integrated manner at a consistent level of complexity.

Students face three main challenges in learning anatomy. First, this subdiscipline of the biological sciences requires mastering many different detail heavy explanations to understand each topic. Students find that learning the amount of detailed knowledge required is overwhelming. This is not only because of the discreet nature of each body of fact that they must know, but also because the effects of many highly detailed explanations of structures or functions upon each another are all essential to comprehend the larger conceptual framework.

The second problem is to understand the timing of anatomical and functional activities in the body. Inconveniently, many of these occur simultaneously. Each student must engage in the mental juggling of ideas to follow the anatomical pathways they must comprehend for each topic.

The third requirement of students seeking to master the topic is to learn to build a hierarchy of ideas to know when each component of the matrix comes into play. This failing is exacerbated by the No Child Left Behind philosophy of "teaching to the test" (see, e.g., [8]). This teaching method is defined as students memorizing by rote an answer to a specific question. There is no overlap of ideas which would provide context for the information. Equally significant, the relative contribution to the entire picture of events as a summation of these ideas, concepts or processes is not defined. Therefore, all idea complexes have equal importance and no specific relationship can be discerned among them. As a result, students are overwhelmed with what they consider to be disparate unrelated bits of information.

Standard textbooks for these courses, e.g., the popular ones by Tortora and Nielsen [10] for lower-level courses or Moore et al. [6] for upper-level courses, do not help students overcome these challenges. Even the available supplements to the most commonly used texts merely reiterate the same information. The forms of the exercises may differ, but the manner in which the content is presented remains the same. In some cases, supplement and test bank questions and answers, even with novel accompanying diagrams or other illustration forms, repeat the information already presented. While repetition is an aid to learning, it fails to generate a deeper understanding of the material inherent in the course.

2 Causal Concept Maps

The term "concept map" can refer to a large number of diagrammatic approaches to human knowledge [7]. Because causality is one of the main concepts underlying the material students need to learn, we were specifically interested in concept maps that could represent several different forms of causality. We named our approach *causal concept maps*. Since an understanding of hierarchical levels is another core concept that students have trouble learning from conventional textbooks, our concept maps are hierarchical, i.e., each item can be considered as a process which could have its own lower-level causal concept map, similar to the decomposition of activities in UML activity diagrams [3, ch. 11]. These aspects of the system are important for different reasons; while causality is fundamental to the biological processes, hierarchy is more important for teaching as students have difficulty connecting seemingly disparate pieces of information.

In order to design a system that could process these causal concept maps, we needed to develop a rigorous definition. A causal concept map is composed of rectangles and arrows, with rectangles representing components of the system and arrows representing relationships between those components. There are two kinds of rectangles: simple rectangles and those with double bars. A simple rectangle represents a single component relevant to an anatomical model of the cardiovascular and respiratory systems. The double bars indicate that a significant summary of components and relationships has been made and is contained within the double-barred box. There are also four kinds of arrows in the diagram: a plain, black arrow; a white, hyphenated arrow; a white, equivalency arrow; a curved, black arrow. A plain, black arrow represents a causal relationship. A white, hyphenated arrow represents that one component permits another to occur. A white, equivalency arrow indicates a mathematical equation; the components involved form the expressions. Finally, a curved, black arrow means "is sensed by," indicating a causal relationship of a different variety: a chemical relationship noticed in the blood.

Rectangles contain information related to the component they describe. Names of the components appear in lowercase letters unless they are abbreviated. Within this description, components referred to by name will be italicized. Additionally, there are potentially two pieces of information within parentheses inside a rectangle. The type of relationship a component has with the component that preceded it, direct or inverse respectively, is indicated by a capital I for increasing or a capital D for decreasing. There may also be a synonym or abbreviation contained within parentheses inside a rectangle, e.g., *intercostal muscle contraction amount* may also be known as "muscle recruitment." The small, circled numbers next to some of the rectangles indicate the number of components with which a particular rectangle has a causal relationship. This is only done when the number affected is greater than one.

The choice to summarize some of the components with the double-barred box notation can be explained as follows: by focusing on components relevant to an anatomical study of the cardiovascular and respiratory systems, cognitive load on students could be reduced and a consistency of scale achieved across the diagram. Additionally, there is a time constraint to consider: as other topics must be covered in the course as well, only the content which is necessary appears. As introductory undergraduate anatomy courses provide an anatomical overview of the cardiovascular and respiratory systems instead of a physiological one, *cellular metabolism* is contained within a single, doublebarred box as the elements within constitute the field of histology. On the other hand, *respiratory volume*, another double-barred box, is expanded as its composite elements fit properly within the field of anatomy. One may see the five components which comprise *respiratory volume* expanded along the bottom of the diagram.

Entry to the concept map is through *oxygen demand/oxygen supply* at the top of the diagram. The concept map both begins and ends with *oxygen demand/oxygen supply* as the body is a homeostatic loop, in other words tending towards stability. In general, the concept map may be read top-to-bottom, until the point at which it loops back to the beginning with the *arterial system carrying capacity* box on the left side of the diagram and the *respiration* box on the right side of the diagram.



Fig. 1. Causal concept map for our system.

3 An ITS Based on a Causal Concept Map

We are developing an ITS platform that can be used as a basis for any ITS based on a causal concept map of the style described above. We are building an ITS for the cardiovascular and respiratory systems using this platform to see how well it does as an intelligent adjunct to a conventional textbook. We plan to test it on students taking

Table 1. Sample problems from our ITS.

Scenario:

Mr. C. is walking to the bus stop when he sees the bus. He starts running to catch it, but feels short of breath and has to stop and rest.

Question 1: (multiple choice)

What is the first event represented in the model in Mr. C's physiology that caused him to feel short of breath?

Question 2: (via GUI)

List all of the events in the model, in the order in which they occur, that explain why Mr. C felt short of breath.

Functional Human Anatomy in Fall 2019. Our ITS is based on the conceptual architecture outlined by VanLehn [11] and used in earlier causal concept map based ITSs such as Circsim-Tutor [2]. Circsim-Tutor is simpler than the current system in multiple ways. Its concept map only contains about 10 items at a single level with one type of causality. All of the relationships it covers are within cardiovascular physiology, and the system can only ask the user a small number of distinct questions.

Our system is based on a set of scenarios based on the topics covered by the causal concept map in Figure 1. A sample scenario is shown in Table 1. Each scenario comes with a set of questions; two sample questions are shown in Table 1. The system is cloud-based and uses a GUI. Some questions rely on the GUI for complex answer handling, such as sorting a list of items, while others allow students to type single words or short answers. When a student gets a question wrong, the system can choose one of several kinds of hints. The system identifies the correct answer by tracing the scenario in the concept map just as it is asking the student to. Similarly, the concept map can be used to generate hints, using algorithms similar to those suggested by Hume et al. [4] and Zhou et al. [12].

4 Content

Compared to traditional textbooks, the use of a causal concept map based ITS provides three obvious benefits to students of anatomy. Causal concept map based ITSs provide students with opportunities to connect facts and concepts learned separately, require students to build hierarchies among these same elements, and finally emphasize to students the simultaneously occurring nature of the processes detailed.

Returning to the example of the diaphragm, one might imagine a student reading about its role in the cardiovascular and respiratory systems from the glossary of a textbook: diaphragmatic contraction amount is the amount of contraction in the parachuteshaped muscle which encircles the base of the lungs and comprises the major muscle involved in breathing. While there are several important pieces of information here, it is hardly a complete picture. The diaphragm is the major muscle involved in breathing, but there are others. The process of breathing is mentioned, but its mechanics are not detailed. Furthermore, the system which controls the muscles themselves is omitted entirely. Without a method for integrating so many pieces studied in isolation, the higher levels of Bloom's taxonomy [1] will often be unreachable.

A causal concept map based ITS provides students with the same facts and concepts as a textbook, but with an opportunity to make enhanced connections among these elements through testing (see, e.g., [9]). Students answer questions, receive hints, and interpret materials, which allows not only flexible retrieval of knowledge but organization as well. Rather than simply memorizing that a chain of events in the nervous system exerts sympathetic, or unconscious, control over the lungs, students are able to see how structure relates to function by connecting the different components through the interactive questioning provided by the ITS. Consulting the expansion of *respiratory volume* box in the diagram, *diaphragmatic muscle contraction amount* can be seen to affect *intercostal muscle contraction amount*, allowing breathing to take place passively as the increase in *thoracic space* lowers interior pressure relative to the atmosphere, all of which is permitted by a *chain of events in the nervous system*. This increased grasp of the material allows students to evaluate information and see the connections between situations, for example, a change in altitude, an increase in activity level, or a faulty pacemaker.

In this way the ITS requires students to form hierarchies among these facts and concepts by answering questions related to the relationships among the elements, thereby connecting pieces of knowledge. Within the hierarchy of the cardiovascular and respiratory systems, *diaphragmatic muscle contraction amount* can be seen to be a part of the *respiratory volume* box, which itself composes half of the *respiration* box. All three of these components are permitted by the *chain of events in the nervous system* box, which can itself be seen to be the eventual result of an increase in *oxygen demand/oxygen supply* which the increase in *respiration* permits. There are so many processes within processes that their interaction and simultaneous occurrence resist simple, linear description. This issue is exacerbated by the regional versus systemic approaches to anatomy.

With a systemic approach, students come to understand deeply the innerworkings of a single system throughout the entire body. To achieve this understanding however, much of the rest of the body of knowledge must be sacrificed. With a regional approach, students study the components which comprise a particular region of the body. While the interaction of the various components in the region of the chest, for example, might be well understood, how these components fit into the larger systems which comprise the body remains elusive. The causal concept map based ITS requires students to absorb both types of information through discussion on which series of components are encompassed by *respiratory volume*, on whether a *chain of events in the nervous system* caused *respiratory volume* to change and on what type of relationship *respiratory volume* has with *respiration*.

This leads to the final benefit: the system emphasizes to students the simultaneity of these processes. While breathing continues on the right side of the diagram through *respiration*, the heart continues to pump blood on the left via *cardiac output*, the

concurrency all the more apparent when the pieces are placed side by side. The process of breathing forms a continuous loop, air flowing into the space of lower pressure, into the expanded lungs, or out of the compressed lungs and into the atmosphere. The heart continuously beats, the blood flowing away through the arteries and back through the veins. It is only where these two loops overlap that gas exchange occurs, carbon dioxide is expelled as waste as the blood is reoxygenated, the vital process of cellular metabolism allowed to continue and the body permitted to handle the increase in activity level, the increase in altitude, or more abstractly, the increased oxygen demand.

The following is a description of the components themselves.

• % Carbon Dioxide Saturation. Percentage of carbon dioxide saturation refers to the amount of carbon dioxide saturated blood relative to total blood that can be measured in one's arteries. An increase in carbon dioxide saturation is caused by both *cellular metabolism* as well as an increase in *oxygen demand/oxygen supply* as the muscular system produces carbon dioxide as a byproduct via cellular metabolism. Changes in carbon dioxide saturation are sensed by the *carotid body*, a small cluster of chemoreceptors near the carotid artery in the neck.

• % Oxygen Saturation. Percentage of oxygen saturation refers to the amount of oxygen saturated hemoglobin relative to total hemoglobin that can be measured in one's arteries, a normal range being 94 to 99 percent. A decrease in oxygen saturation is caused by increases in oxygen demand/oxygen supply as well as cellular metabolism as energy is produced at the cellular level with oxygen as a reactant.

• Arterial System Carrying Capacity. This refers to the ability of the arteries to expand in response to increased blood pressure as cardiac output increases. As blood circulation increases in the lungs, arterial system carrying capacity increases in response to accommodate. A chain of events in the nervous system also permits this increase in arterial system carrying capacity by regulating blood pressure via the medulla oblongata. An increase in arterial system carrying capacity permits an increase in oxygen demand/oxygen supply as more oxygen-rich blood is carried away from the heart and back to the body.

• *Blood Circulation in Lungs*. Blood circulation in the lungs is the flow of blood through the pulmonary arteries and pulmonary capillary beds where gas exchange occurs. An increase in *blood circulation in the lungs* is produced by an increase in *cardiac output* as the heart pumps more blood through the pulmonary arteries. An increase in *blood circulation in the lungs* causes an increase in *arterial system carrying capacity* as the increased amount of blood being pumped out of the heart and into the lungs causes an increase in *arterial system.*

• Cardiac Output (HR*SV). Cardiac output is equivalent to the expression heart rate multiplied by stroke volume. An increase in cardiac output results in an increase in blood circulation in the lungs and correlates with increases in respiratory rate and respiratory volume. An increase in cardiac output causes an increase in blood circulation in the lungs as additional blood is pumped out of the heart and through the pulmonary arteries. This increase in cardiac output also correlates with increases in respiratory rate as well as respiratory volume as additional oxygen and carbon dioxide are able to be exchanged due to the increased blood flow through the pulmonary capillary beds. Increases in either heart rate or stroke volume or both cause increases in cardiac

output as *cardiac output* is equivalent to the product of heart rate multiplied by stroke volume.

• *Carotid Body*. The carotid body is a small cluster of chemoreceptors in the neck near the carotid artery which sense changes in carbon dioxide saturation in the blood. Sensing a change in carbon dioxide saturation, the *carotid body* causes a *chain of events in the nervous system* which regulates both breathing and blood pressure.

• *Cellular Metabolism.* This refers to the complex set of chemical changes involved in energy production which require oxygen and produce carbon dioxide as a byproduct. *Cellular metabolism* causes decreases in oxygen saturation and increases in carbon dioxide saturation.

• Chain of Events in Nervous System. The events which take place in the nervous system that relay messages from the carotid body to the brain stem (medulla oblongata) and then to the appropriate sites within the body. The chain of events in the nervous system is caused by the carotid body as it senses changes in levels of carbon dioxide within the blood. The chain of events within the nervous system permits four events which also impact the chain of events in the nervous system: increases in heart rate, stroke volume, respiratory rate, and respiratory volume. This is because this chain of events includes the vagus nerve which exerts sympathetic, or unconscious, control over the heart and lungs but also receives feedback reflecting the anatomical changes. The chain of events in the nervous system also permits an increase in arterial system carrying capacity.

• *Diaphragmatic Muscle Contraction Amount*. The amount of contraction in the parachute-shaped muscle which encircles the base of the lungs and comprises the major muscle involved in breathing. Increases in contraction of the diaphragm causes recruitment of the intercostal muscles to assist with breathing, increasing *thoracic space* and the *volume of air inhaled*. Relaxation of the diaphragm increases pressure which causes expiration (exhalation of air).

• *Heart Rate (HR). Heart rate*, or pulse, is the number of times one's heart beats per minute. Increases in *heart rate* are permitted by a *chain of events within the nervous system* and are caused by increases in *oxygen demand/oxygen supply*. Along with *stroke volume*, increases in *heart rate* are equivalent to increases in *cardiac output*.

• Intercostal Muscle Contraction Amount. The amount of contraction in the muscles situated between the ribs. Intercostal muscles are recruited by the diaphragm to assist with breathing. Contraction of the intercostal muscles increases *thoracic space* and decreases the pressure within, causing inhalation.

• Oxygen Demand/Oxygen Supply. Equivalent to a change in altitude, a change in activity level, or muscle contraction among other things, the ratio of oxygen demand to oxygen supply refers to the amount of oxygen required by the body to perform an action or movement, with the condition of being at rest considered the baseline. For example, an increase in activity level is equivalent to more, faster and harder muscle contraction, and itself causes six things to occur within the system: a decrease in the *percentage of oxygen saturation*, an increase in the *percentage of carbon dioxide saturation*, an increase in *heart rate*, an increase in *stroke volume*, an increase in *respiratory rate*, and an increase in *respiratory volume*.

Increases in *oxygen demand/oxygen supply* cause changes in levels of oxygen and carbon dioxide as these resources are consumed and produced via cellular metabolism. Increases in *oxygen demand/oxygen supply* cause increases in *heart rate* and *stroke volume* to increase blood flow to the muscles to provide the oxygen necessary to support the additional activity. Increases in *respiration* and *arterial system carrying capacity* permit an increase in *oxygen demand/oxygen supply* because increases in *arterial system carrying capacity* allow more blood to be transported back to the lungs where increases in *respiratory rate* and *respiratory rate* contribute to oxygenation.

• *Respiration.* The act of breathing. Increases in *respiration* are equivalent to increases in either *respiratory rate* or *respiratory volume* or both. Increases in *respiration* permit increases in *oxygen demand/oxygen supply* as additional gas exchange occurs, delivering oxygenated blood via the arterial system.

• *Respiratory Rate.* The number of breaths that one takes per minute. An increase in *respiratory rate*, along with *respiratory volume*, is equivalent to an increase in *respiration*. Increases in *respiratory rate* are permitted by a *chain of events within the nervous system* and correlate with increases in *cardiac output* as additional blood flowing through the pulmonary capillary beds allows for increased gas exchange. Increases in *oxygen demand/oxygen supply* cause increases in *respiratory rate*.

• *Respiratory Volume.* The total amount of air within a single cycle of inspiration (inhalation) and expiration (exhalation). An increase in *respiratory volume*, along with increases in *respiratory rate*, are equivalent to increases in *respiration*. Increases in the volume of air in the respiratory cycle are permitted by a *chain of events in the nervous system* and caused by increases in *oxygen demand/oxygen supply*.

• Stroke volume (SV). Stroke Volume is the amount of blood pumped by the heart in one stroke, or beat. Increases in *stroke volume* are permitted by a *chain of events* within the nervous system and caused by increases in oxygen demand/oxygen supply. Along with heart rate, increases in stroke volume are equivalent to increases in cardiac output.

• *Thoracic Space*. The amount of space within the cavity of the chest. An increase in *thoracic space* causes an increase in the *volume of air inhaled* as pressure within the lungs decreases. An increase in *thoracic space* is caused by an increase in *intercostal muscle contraction amount*.

• Volume of Air Exhaled. Similar to Volume of Air Inhaled.

• Volume of Air Inhaled. The amount of air inhaled in a single breath. The volume of air inhaled increases as thoracic space increases. This is because pressure within the lungs decreases due to the increased space. An increase in the volume of air inhaled causes an increase in the volume of air exhaled. This is due to changes in pressure within the lungs, air flowing into the area of lower pressure. During exhalation, pressure within the lungs is greater than the atmosphere so air flows out. After exhalation, pressure within the lungs is less than the atmosphere so air flows back in, increasing the volume of air inhaled.

5 Conclusions and Future Work

Using an intelligent tutoring system which utilizes hierarchical causal concept maps is a novel approach to solving a problem that has been resistant to previous standard methods within the field of anatomy. Undergraduate anatomy students have trouble connecting facts and concepts learned separately, building hierarchies among those concepts, and understanding that the causal relations between these concepts happen simultaneously.

After formalizing the notion of hierarchical causal concept maps, we have developed ITS software that can process multiple scenarios using a causal concept map for the cardiovascular and respiratory systems. We have written a simulator for this system [5] and are also planning to test the system with students taking a variety of anatomy and physiology classes.

References

- Bloom, B. Taxonomy of Educational Objectives. Handbook I: The Cognitive Domain. David McKay, New York (1956).
- Evens, M., Michael, J.: One-on-One Tutoring by Humans and Computers. Erlbaum, Mahwah, NJ (2006).
- 3. Fowler, M. UML Distilled: A Brief Guide to the Standard Object Modeling Language. 3rd edn. Addison-Wesley, Boston (2004).
- Hume, G., Michael, J., Rovick, A., Evens, M.: Hinting as a Tactic in One-On-One Tutoring. Journal of the Learning Sciences, 5(1):23-47 (1996).
- Jasti, M., Freedman, R.: Using A Simulator to Choose the Best Hints in a Reinforcement Learning-Based Multimodal ITS. In: 15th International Conference on Intelligent Tutoring Systems (2019).
- Moore, K., Agur, A., Dalley II, A.: Clinically Oriented Anatomy. 8th edn. Wolters Kluwer, Philadelphia (2017).
- Novak, J.: Learning, Creating, and Using Knowledge: Concept Maps as Facilitative Tools in Schools and Corporations. 2nd edn. Routledge, New York (2010).
- 8. Popham, J.: Teaching to the Test? Educational Leadership, 58(6): 16-20 (2001).
- 9. Roediger III, H., Putnam, A., Smith, M.: Ten Benefits of Testing and Their Applications to Educational Practice. Psychology of Learning and Motivation, 55: 1-36 (2011).
- Tortora, G., Nielsen, M. Principles of Human Anatomy. 14th edn. Wiley, Hoboken, NJ (2016).
- VanLehn, K.: The behavior of tutoring systems. International Journal of Artificial Intelligence in Education, 16(3): 227-265 (2006).
- Zhou, Y., Freedman, R., Glass, M., Michael, J., Rovick, A., Evens, M.: Delivering Hints in a Dialogue-Based Intelligent Tutoring System. In: Proceedings of the Sixteenth National Conference on Artificial Intelligence (AAAI-99) (1999).