Does the Foundational Model of Anatomy ontology provide a knowledge base for learning and assessment in anatomy education?

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***Abstract*—Throughout the development of the Foundational Model of Anatomy (FMA) ontology, one of the use cases put forth has been anatomy education. In this work, we examine which types of knowledge taught to anatomy students can be supported by the FMA knowledge base. We first categorize types of anatomical knowledge, then express these patterns in the form "Given ____, state ____". Each of the 33 patterns was evaluated for whether this type of knowledge is compatible with the modeling and scope of the FMA.**

Keywords—anatomy; ontology; knowledge representation; medical education; nursing education

I. INTRODUCTION

Knowledge of human anatomy is fundamental to the fields of health sciences. Software applications that support the delivery of healthcare services and training of healthcare providers often incorporate anatomical knowledge, but rarely in ways that are computable and reusable. As researchers seek to make software systems more intelligent, opportunities to draw upon knowledge bases of anatomy will increase. As part of this research agenda it is important to examine whether the needs of specific applications can be supported by available knowledge bases.

This paper categorizes the types of knowledge relevant to student learning in university-level courses in human anatomy, and then examines which types are supported by the Foundational Model of Anatomy (FMA) ontology.

II. BACKGROUND

A. *The Foundational Model of Anatomy*

The FMA is both a theory for representing anatomy and a computational artifact [1,2]. It is currently modeled in OWL2 [3]. The majority of the content describes adult human canonical anatomy, although recent work has incorporated developmental anatomy. Because the FMA is a reference ontology, it has not been developed for a specific type of application; rather, it is intended to serve as a knowledge base for diverse applications that need a standardized and computable representation of human anatomy.

The line of research that produced the FMA originated in efforts to engineer knowledge-based systems that use the structure of the human body as a basis for organizing spatial and semantic representations of the body [4,5]. One theme of this work was designing systems to be used in anatomy education. Demonstration projects included systems that support browsing of segmented 2D medical images and 3D anatomical models, including a web-based atlas of interactive 3D graphics known as the Digital Anatomist [6]. The semantic network underlying this system was the precursor to the FMA.

B. *Anatomical education for health science students*

The process by which health science students learn anatomy has traditionally consisted of a combination of cadaveric dissection, two-dimensional illustrations or photographs, and text-based descriptions of anatomical relationships. Like most areas of modern life, computer-based tools have increasingly been integrated into anatomy education. These include computer-based interactive atlases, such as the Visible Human Project, as well as virtual anatomic models that allow students to rotate and visualize structures and relationships in three dimensions. These types of computer-based 3D visualizations can successfully augment more traditional methods of instruction, resulting in improved understanding and retention of anatomic knowledge [7]. As health science schools move towards more streamlined basic science education with a greater emphasis on student-directed learning, computer-based anatomic teaching tools will play an increasing role in anatomy education [8].

If educational applications for learning anatomy make use of common knowledge bases—instead of relying on application-specific catalogues of knowledge—benefits will include greater standardization of terminologies, less duplication of effort in constructing knowledge artifacts, and easier implementation of reasoning capabilities. This paper revisits the potential for the FMA to serve as a knowledge base for education in gross human anatomy, three decades after its conception.

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III. METHODS

A. Identifying knowledge relevant to anatomy education

To capture types of knowledge relevant to learning human anatomy in university-level courses, a variety of educational resources were reviewed. Particular emphasis was given to structured information presented as tables in atlases and review guides [9–11], as well as the content of practice questions [12–14]. Content was examined to identify minimal units of information and general categories of knowledge.

Consider these examples:

- A table describing lymph node groups that provides information about location, afferent lymphatic structures, efferent lymphatic structures, and regions of the body drained (from [11]).
- A review question, "The ___ returns blood [to the heart] from body regions above the diaphragm" (from [12]).

Although these examples describe different anatomical systems, they are similar in that they both refer to the connectivity and spatial location of structures.

During the process of identifying units of information and developing categories, a category was created if two or more examples of a pattern of knowledge were found within the sampled content. These categories were expressed as assessment questions using patterns in the form "Given ____, state ____" in order to make explicit the prompt and the knowledge to be recalled. An example of a pattern is "Given a structure, state its parts".

B. Comparing types of assessment questions to the content and structure of the FMA

Each category of assessment questions was compared with the modeling and scope of the FMA. Effort was directed toward determining whether the type of knowledge in the assessment questions could be retrieved from the FMA, not determining whether the FMA currently contains the content necessary to answer specific questions.

IV. RESULTS

Five broad categories of anatomical knowledge were identified (see Table 1). Questions were organized into 17 subcategories and expressed through a total of 28 patterns. Table 1 also provides examples of specific questions for each pattern and an assessment of whether the FMA could serve as a source for each type of knowledge.

This analysis shows that the FMA is well-suited to representing knowledge about synonyms of terms, classification of anatomical structures, parts of structures, and connectivity between structures. As expected, the FMA is not a suitable knowledge base for questions about the qualities of anatomical structures (such as morphology or variation within the population).

For the types of knowledge that the FMA can support, several factors may complicate efforts to directly apply the FMA to educational applications:

A. High granularity of the FMA

Part relationships within the FMA tend to be much more granular than those taught in anatomy courses. For example, Figure 1 (top) shows a question about a part of the urinary bladder. In the FMA, this information traverses three part relationships.

Implications: This high level of granularity in the FMA is appropriate for advanced anatomy courses, but may not be a good fit for learners in basic anatomy courses. But just as advanced learners should be able to understand and reason over high-granularity representations to answer low-granularity questions, it is possible that some types of high-granularity representations in the FMA can be converted to low-granularity representations.

B. High specificity of the FMA

Educational materials may focus on general concepts ("ventral and dorsal roots merge to form a spinal nerve"), while the FMA tends to represent knowledge with greater specificity (such as specific ventral and dorsal roots).

Implications: The class hierarchy may provide an avenue for representing knowledge applied to many individual structures. (For example, "Muscle organ" *has regional part* "Distal tendon".) However, because properties of class are inherited by all its subclasses, there is a danger that a general anatomical principle will not be true for every subclass.

C. Formal and explicit representation of the FMA

Educational materials often make use of assumptions and unwritten knowledge. Making this knowledge explicit, as required by the FMA, can introduce an expected level of complexity. As show in Figure 1 (bottom), answering a question about the passage of air through the nose and into the pharynx using the FMA requires that the nasal cavity is explicitly recognized as a part of the nose. A medical student has tacit knowledge that movement of air through the respiratory system (at the level of gross anatomy) takes place within tubes and cavities, and would immedicately recognize that this question refers to air-filled spaces—even if he or she did not conceive of "nasal cavity" as an anatomical structure.

Implications: Directly translating the FMA content into educational contexts is largely inappropriate because it risks directing students' attention toward modeling details of the FMA, rather than on building upon their existing understanding of anatomy. However, it may be appropriate to use explicit FMA representations as a supplement to less-detailed representations as a way to help students construct and deepen their knowledge of anatomy.

D. Translating to the language of the FMA

As noted in previous work to test the FMA against anatomy examination questions [15], common English-language expressions and terms often need to be translated by someone familiar with the FMA. An example is shown in Figure 1 (top), where the phrase "is located in" translates to "is regional part of" and "is constitutional part of".

Implications: The precision of relationships used in the FMA may be helpful in stimulating students to think more deeply

TABLE I. CATEGORIES OF ASSESSMENT QUESTIONS FOR ANATOMICAL KNOWLEDGE

Category of assessment question	**Suitable for FMA**
Category 1: Representations and real anatomy *Understanding visual and semantic representations and their relation to real anatomy*	
1a. Cadaver "pin test" Given a structure marked within a cadaver, state the corresponding anatomical term.	No
1b. Translating between visual representations and verbal representations Given a visual representation of a structure, state the corresponding anatomical term. [And reverse: Given an anatomical term, identify the structure in a visual representation.]	No
1c. The language of anatomy Given a directional term, state the definition. [And reverse.] • Superficial: toward the surface • Distal: away from the center Given a plane, state the definition. [And reverse.] • Median: separates right lateral and left lateral regions at midline • Transverse: separates superior and inferior regions Given an anatomical root word, state the definition. [And reverse.] • Brachial: of the arm • Orbital: of the eye Given a structure, state a synonym. • Pharyngotympanic tube: Eustachian tube • Nostril: naris	No No No Yes, synonyms are provided.
Category 2: Classification *Understanding how categories are used to describe anatomy, as well as characteristics of members of categories*	
2a. General vs. specific Given a specific structure, state the type of structure to which it belongs. • Elbow joint: synovial joint • Frontal bone: flat bone • Lateral meniscus: cartilage Given a type of structure and a defining characteristic, state the specific structure. • Nerve that innervates the foot and leg: sciatic nerve • Fluid in the lymphatic system: lymph • Joint that is the largest and most complex in the body: knee joint	Yes. Available in the class hierarchy No, unless encoded through class hierarchy or other relationships.
2b. Cardinality Given a type of structure, state how many are present in the (canonical) body. • Permanent teeth: 32 • Major calyces per kidney: 2–3 • Layers of meninges surrounding brain and spinal cord: 3	No, although some information may be implied through the class hierarchy.
Category 3: Canonical structure *Understanding the location, composition, and demarcation of structures*	
3a. Whole-part relationships Given a structure, state its parts. • Mandible: left ramus, right ramus, body of mandible • Lymph node: cortex, medulla • Cortex of lymph node: superficial cortex, paracortex Given a region of a structure, state the indicated part of that structure. • Lowest portion of the brainstem: medulla oblongata • Triangular divisions of the medulla of the kidney: renal pyramids	Yes. Available in regional and constitutional part hierarchies. No, although some information may be available in definitions.

Given a structure, state the types of tissues that compose it. • Skin: epidermis, dermis • Nasal cartilage: hyaline cartilage	Yes. Available in the constitutional part hierarchies.
3b. Regional location of structure Given type of structure and region of the body, state the specific structures of that region. [And reverse.] • Muscles of the neck: longus capitis, longus colli, rectus capitis anterior, … • Foramen of the skull: right/left mental foramen, right/left infraorbital foramen, … • Lymph node groups of head and neck: submental, submandibular, occipital, …	Yes, if a region has been represented. For example, classes such as “Musculature of hand” have members that are individual muscles.
3c. Spatial relationships among structures Given a structure and a spatial relation, state the associated structure(s). • Spinal cord *passes through*: foramen magnum • Femoral triangle *contains*: femoral vessels, femoral nerve, lymph nodes • Subarachnoid space *contains*: cerebrospinal fluid • Femoral artery *bisects*: femoral triangle • Serous pericardium *surrounds*: heart • Annular ligament *surrounds*: radial head • Deltopectoral triangle *has superior boundary*: deltoid • Ribcage *is superficial to*: lungs	Most, using relationships such as *surrounds, lateral to, contains.*
Given two structures, state the structure positioned between them. [And reverse.] • *Between* the visceral and parietal layers of the peritoneum: peritoneal cavity • *Between* the lungs, immediately anterior to the heart: thymus • *Dividing* the right and left sides of the nasal cavity: nasal septum	No
Given a structure (artery, vein, or nerve), state the structures it encounters along its course. • Internal iliac artery: passes over pelvic brim and descends into pelvic cavity	No
3d. Connectivity between structures Given a structure and type of connectivity, state the associated structure(s). • Scapula *articulates with*: clavicle, humerus • Via the coronal suture, the frontal bone *articulates with*: right/left parietal bones • Carpometacarpal joint of thumb *connects*: trapezium and metacarpal of thumb • Anconeus *has origin*: lateral epicondyle • Anconeus *has insertion*: lateral side of olecranon, upper ulna • Anconeus *has innervation*: radial nerve • Right subclavian trunk *drains into*: right lymphatic duct • Occipital artery *has origin (or source)*: external carotid	Yes, using relationships such as *articulates with, has origin, has insertion, drains into.*
Given two or more structures, state the structure they join or merge to form. • Ventral and dorsal roots *merge to form*: spinal nerves	An alternative modeling scheme using branches and tributaries (as regional parts) is employed.
Given a structure, state the two or more structures it branches, bifurcates, or divides into. • After exiting the vertebral column, each spinal nerve *divides into*: dorsal ramus, ventral ramus, meningeal branch, communicating rami • Trachea *bifurcates into*: right and left main bronchi	An alternative modeling scheme using branches and tributaries (as regional parts) is employed.
3e. Clinical regions and landmarks (points, lines, borders) Given a region or structure, state the associated clinical regions. • Abdomen: epigastrium, umbilical region, suprapubic region, right and left lumbar regions …	Yes, if modeled as regional parts.
Given a structure, state the associated landmarks. [And reverse.] • Points of the skull: right and left euryon, right and left coronale, right and left auriculare, … • T2 (second thoracic vertebra): superior border of scapula	Some. For example, the class hierarchy contains subclasses of “Anatomical point of skull”. Other landmarks may be captured using the scheme 3D structures are bounded by 2D surfaces, bounded by 1D lines, bounded by 0D points.
3f. Morphology Given a structure, describe its form. • Duodenum: c-shaped part of the small intestine • Vertebral foramen of cervical vertebra: triangular space • Mandibular alveoli: sockets (for teeth)	No, unless available in definition.

Category 4: Variation in structure *Understanding variations in human anatomy*	
4a. Sexual dimorphism Given a structure, describe the morphological differences between female and male structures. • Sacrum: female sacra tend to be wider, shorter, and less curved than male sacra • Pelvic inlet: circular in females, heart-shaped in males	No
4b. Anatomical variation Given a structure, describe common variations. • Branches from the aortic arch: in the most common variant, the left common carotid artery arises from the brachiocephalic trunk (instead of the aortic arch itself) • Sternalis: a muscle parallel to margin of the sternum, present in less than 10% of population	No
Category 5: Developmental anatomy *Understanding structural changes during gestation and early childhood*	
5a. Development of structures Given a structure, state the structure(s) it develops into or becomes part of. [And reverse.] • Urogenital ridge: pronephros, mesonephros, metanephros • Neural tube: brain, spinal cord	Some. The relationships *derives, matures into, and transforms into* have been used in recent work.
5b. Germ layer origins Given a structure, state the germ layer it developed from. • Kidney: intermediate mesoderm • Epithelium of gastrointestinal track: endoderm	Some. The relationship *germ origin* has been created.
5c. Developmental homologues in males and females Given a (male/female) structure, state the developmentally homologous (female/male) structure. • Ovary: testis • Cowper's gland: Bartholin's gland	No
5d. Timing of developmental events Given a structure, state the stage (or time interval) at which it is present. [And reverse.] • Three primary brain vesicles: 4th week • Implantation: about 7 days	Some. The relationship *developmental stage of* has been used in recent work

about anatomical relationships, but may not be directly relevant to the needs of students in basic anatomy courses.

V. CONCLUSION

This work helps to make explicit ways in which the FMA knowledge base could (and could not) support learning within a university-level anatomy course. The work will assist developers of educational applications in identifying types of anatomical knowledge, as well as recognizing opportunities for making use of a knowledge base such as the FMA.

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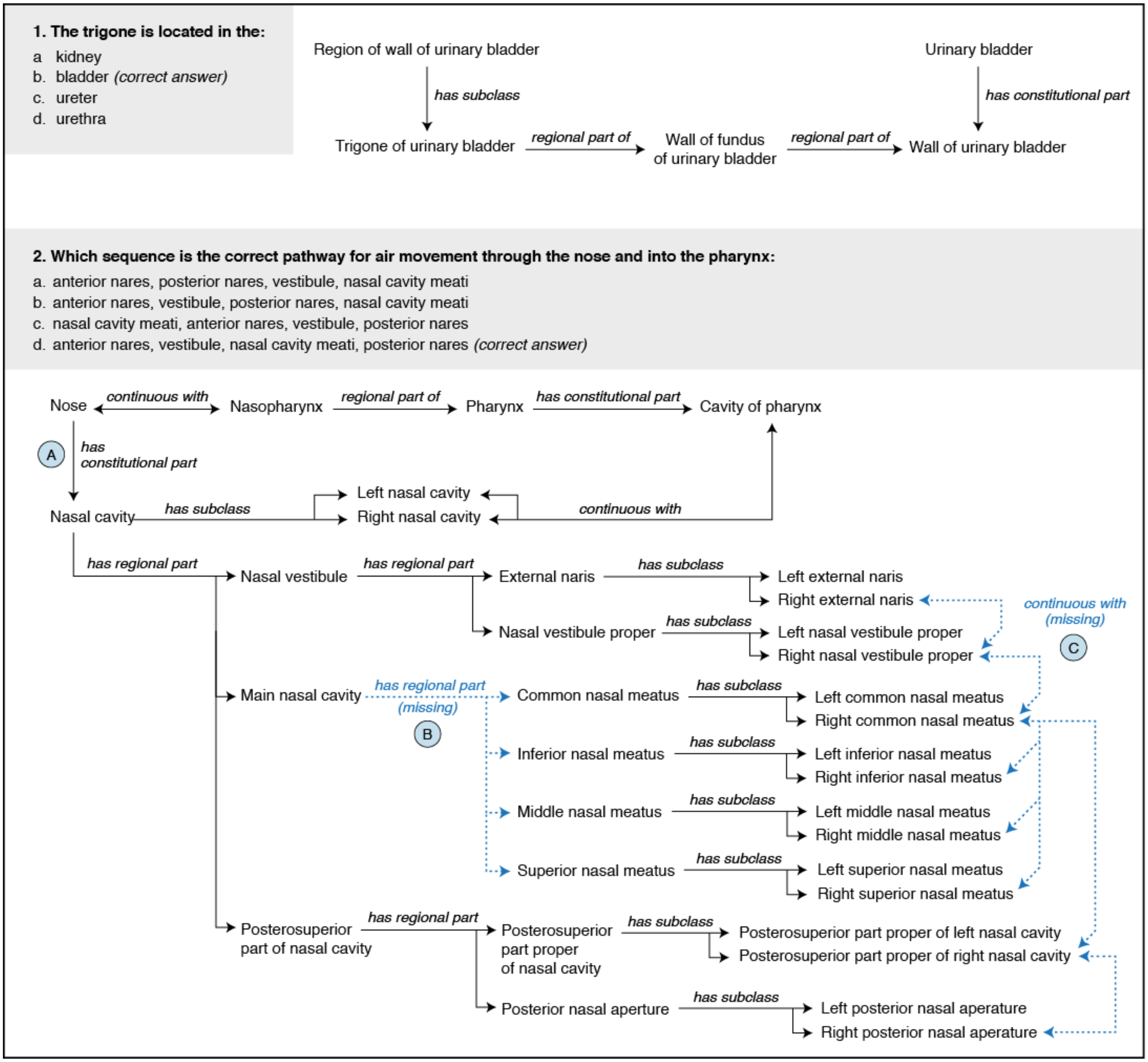

1. The trigone is located in the:

a kidney
b. bladder *(correct answer)*
c. ureter
d. urethra

2. Which sequence is the correct pathway for air movement through the nose and into the pharynx:

a. anterior nares, posterior nares, vestibule, nasal cavity meati
b. anterior nares, vestibule, posterior nares, nasal cavity meati
c. nasal cavity meati, anterior nares, vestibule, posterior nares
d. anterior nares, vestibule, nasal cavity meati, posterior nares *(correct answer)*

Fig. 1. Two examples comparing review questions (from [12]) with content from the FMA. Example 1 (top) contrasts the language of the question ("is located in") with the formal modeling in the FMA. The term "trigone" requires knowledge of the context—it could refer to either the Trigone of urinary bladder or the Trigone of lateral lemniscus (a region of the metencephalon) in the FMA. Example 2 (bottom) makes use of knowledge that the nasal cavity is a constitutional part of the nose (A), the regional parts of the nasal cavity (B), and continuity relationships (C). Dotted blue lines indicate information not currently available in the FMA.

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