The qualitative and time-dependent character of spatial relations in biomedical ontologies

Thomas Bittner[1,3,4] **and Louis J. Goldberg**[2,3]
[1]Department of Philosophy and Department of Geography,
[2]Departments of Oral Biology and Oral Diagnostic Sciences, School of Dental Medicine,
[3]New York State Center of Excellence in Bioinformatics and Life Sciences
[4]National Center of Geographic Information and Analysis (NCGIA)
State University of New York at Buffalo
{bittner3,goldberg}@buffalo.edu

Abstract

The formal representation of mereological aspects of canonical anatomy (parthood relations) is relatively well understood. The formal representation of other aspects of canonical anatomy like connectedness relations between anatomical parts, shape and size of anatomical parts, the spatial arrangement of anatomical parts within larger anatomical structures are, however, much less well understood and only partial represented in computational anatomical ontologies. In this paper we propose a methodology of how to incorporate this kind of information into anatomical ontologies by applying techniques of qualitative spatial representation and reasoning from Artificial Intelligence. As a running example we use the human temporomandibular joint (TMJ).

INTRODUCTION

Anatomical ontologies are formal representations of facts about the major parts of canonical anatomical structures, the qualitative shapes of those parts, and qualitative relations between them [24, 19, 13, 31].

The formal representation of mereological aspects of canonical anatomy (parthood relations) is relatively well understood [16, 32, 13], and has been implemented in computational medical ontologies like the FMA [23], GALEN [22], and SNOMED [33]. On the other hand, the formal representation of other aspects of canonical anatomy like connectedness relations between anatomical parts, shape and size of anatomical parts, the spatial arrangement of anatomical parts within larger anatomical structures are less well understood and only partially represented in computational anatomical ontologies. In this paper we propose a methodology of how to incorporate this kind of information into anatomical ontologies.

Following [24] we stress here the importance of recognizing the qualitative nature of *all* facts represented in anatomical ontologies such as the FMA. It is impossible to quantitatively describe aspects of shape and spatial arrangement of canonical anatomy. There is too much variation between the actual shapes and metric arrangements of particular structures among particular human beings. Moreover it is the very nature of many anatomical structures to change in shape and spatial arrangement over time: the heart beats, the jaw opens and closes, etc.

Qualitative representations of canonical anatomy take advantage of the fact that despite the variations and changes in size, shape, distance, and spatial arrangement, at the macroscopic anatomical level [24], all normal instances of the same biological species are qualitative copies of each other. In all canonical anatomical structures certain parts need to be present. These parts need to have certain qualitative shape features (convex parts, concave parts, other landmark features, etc.), their size must be within certain limits, and certain qualitative relations need to hold between those parts: some parts are connected to others, some part are disconnected from others, some parts (like articular discs) need to be between other parts (like the bones in synovial joints) etc.

In this paper we give an overview of the most important of those relations. We also demonstrate how the changes in shape and arrangement can be specified using qualitative spatial relations. In addition, we claim that most pathological cases can also be characterized and distinguished from non-pathological cases in terms of qualitative relations: there may be too many or too few parts, parts that are supposed to be connected are disconnected, parts that are supposed to be between other parts fail to be so, etc.

Qualitative representation of, and reasoning about complex systems has a long tradition in Artificial

Intelligence [35, 5, 10]. Cohn and Hazarika [8] stress that the essence of qualitative representations is to find ways to represent continuous properties of the world by discrete systems of symbols. As Forbus [14] points out, one can always quantize something continuous, but not all quantizations are equally useful because the distinctions made by a quantization must be relevant for the kind of reasoning performed. This is where *formal ontology* comes into play [30]. It will be an important aspect of this paper to show how to discretize continuous domains in such a way that ontologically significant properties are preserved.

For example, to qualitatively model the behavior of water at different temperatures the continuous domain of temperature is discretized by introducing landmark values: temperature landmark 1 (TLM1) the temperature at which water changes from its solid state to its liquid state and (TLM2) the temperature where water changes from its liquid state to being a gas. These landmark values bound intervals: for example, (TI1) the interval of temperatures at which water is solid, (TI2) the interval of temperatures at which water is liquid, and (TI3) the (half open) interval at which water is a gas. In a qualitative model the behavior of water at different temperatures is described only by referring to the landmark values and the intervals bounded by those values.

An important point is that the landmarks are not chosen arbitrarily. The landmarks represent *significant changes* in the domain at hand, while within the intervals between landmarks no significant changes occur. Thus qualitative representations focus on *ontologically salient features.* For many purposes the above presented qualitative representation of water at different temperatures will be sufficient. For example, in order to transport bottled water from one place to another the exact temperature of the water is irrelevant as long as it does not freeze or change to its gas state since in both cases the bottled water will destroy their containers.

We propose the following methodology for building qualitative representations of canonical anatomical structures that preserve ontologically significant distinctions:

1. Specify and classify the major canonical parts of the structure at hand and establish canonical mereotopological (parthood and connectedness) relations between them;
2. Identify ordering relations between the major parts anatomical structures to qualitatively characterize the spatial arrangement of the parts within the structures;
3. Refine ordering relations between parts by identifying anatomical landmarks and by using landmarks as a frame of reference;
4. Specify qualitative distance relations between landmarks to qualitatively characterize shape and arrangement of the parts.

We will discuss each step below in sequence and use the human temporomandibular joint (TMJ) as a running example. We go into a detailed discussion of how existing techniques of qualitative spatial representation and reasoning from Artificial intelligence can be used and extended to formally and qualitatively represent the mereotopology of anatomical structures, the shape and size of anatomical parts, and the spatial arrangement of anatomical parts within larger anatomical structures. The methods we present here we believe will provide the foundations for the next generation of anatomical ontologies.

ANATOMICAL PARTS AND MEREOTOPOLOGICAL RELATIONS

Parthood relations

At the most basic level of the study of the canonical structure of the TMJ we consider its anatomical parts. Anatomical parts here means, maximally connected parts of non-negligible size (thus cells and molecules are parts of anatomical structures but not anatomical parts). At this macroscopic anatomical level of granularity we will distinguish two kinds of anatomical parts: material parts and cavities. The material anatomical parts of the TMJ at the macroscopic anatomical level of granularity according to [18] are depicted in Figure 1, which shows, in a sagittal section through the middle of the condyle, a TMJ in closed (a) and open (b) jaw position: temporal bone (1), head of condyle (2), articular disc (3), posterior attachment (4), lateral pterygoid muscle (5). Immaterial anatomical parts (cavities) are the superior and inferior synovial cavities, which are depicted as white spaces above and below the articular disc and the posterior attachment. Here we will focus on material parts. For a discussion of immaterial anatomical parts see [12, 27, 19].

A clear understanding of the number and kinds of canonical parts of an anatomical structure is

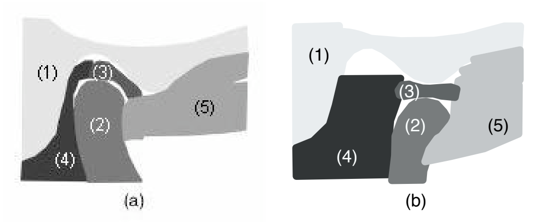

Figure 1: Drawings of (a) the major parts of a TMJ in the jaw closed position and (b) the major parts of the same TMJ in the jaw open position.

critical for identifying non-canonical (and potentially pathological) parts such as tumors. Moreover, without a clear understanding of the number of canonical parts it is not possible to recognize the absence of certain parts. In the remainder of this paper we refer to individual anatomical structures and their material anatomical parts as objects.

Parthood is a ternary relation (a relation with three arguments) that holds between two objects x and y and a time instant t. Parthood is a time-dependent relation since anatomic structures can have different parts at different times. For example, in the course of their transition from children to adults, it is normal for people to have different teeth at different times. See, for example, [28] for axiomatic formalizations time-dependent parthood.

In terms of parthood we define the relations of proper parthood and overlap. Object x is a *proper part* of object y at t if and only if x is a part of y at t and y is not part of x at t. For example, at time t the head of Joe's condyle is a proper part of his condyle. Object x *overlaps* object y at time t if and only if there is an object z such that z is part of x at t and z is part of y at t. If x is a (proper) part of y at t then x and y overlap at t. Thus, at time t Joe's condyle and the head of his condyle overlap.

Connectedness relations

The ternary relation of connectedness holds between two objects x and y at a time instant t. Intuitively, x is connected to y at t if and only if x and y overlap at t or x and y are in direct external contact at t. Two regions are connected at t if and only if they share at least a boundary point at t (they may share interior points at t). For a discussion of the wide range of possible formalizations see [34].

Objects x and y are *externally connected* at time t if and only if x and y are in direct external contact at t but x and y do not overlap at t. Externally connected regions share boundary points but no interior points. Objects x and y are *disconnected* at time t if and only if x and y are not connected at t.

We introduce connectedness as a time-dependent relation since anatomic structures can be connected to different (parts of) structures at different times. As depicted in Figure 1(a), at time t_1 the articular disc is (externally) connected to the fossa (a fiat part[1] of the temporal bone). At time t_2, as depicted in Figure 1(b) the articular disc is connected to the articular eminence (another fiat part of the temporal bone).

The following topological relations hold between the five major parts of the TMJ depicted in Figures 1(a) and (b): the temporal bone (1) is externally connected to the posterior attachment (4) and to the lateral pterygoid muscle (5). The condyle (2) is externally connected to the posterior attachment (4) and to the lateral pterygoid muscle (5). The articular disc (3) is externally connected to the posterior attachment (4) and the lateral pterygoid muscle (5).

Permanent parthood and connectedness

Consider the relation of external connectedness between the articular disc and the temporal bone. Clearly, at every time t the articular disc is externally connected (in external contact) to *some* part of the temporal bone. However at different times the articular disc is externally connected (in external contact) to *different* parts of the temporal bone. In Figure 1 (a) the articular disc is externally connected (in external contact) to the fossa, while in Figure 1 (b) the articular disc is externallhy connected (in external contact) to the articular eminence (another fiat part of the temporal bone).

It is important to make explicit that the connectedness relation between the articular disc and the temporal bone is different from the connectedness relation between the articular disc the posterior attachment and the lateral pterygoid muscle: at all times at which the articular disc is connected to the posterior attachment it is connected to the *same* part of the posterior attachment and similarly for the lateral pterygoid muscle. The relation between articular disc and posterior attachment is a relation of *constant or permanent* con-

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[1] A fiat part is a part which boundaries are (partly) the result of human demarcation and do not correspond to discontinuities in reality [29].

nection (articular disc and posterior attachment are 'glued' together by direct connective tissue attachments). On the other hand the relationship between articular disc and temporal bone is such that both are externally connected (in external contact) but the articular disc has the freedom to slide along the surface of the bone.[2]

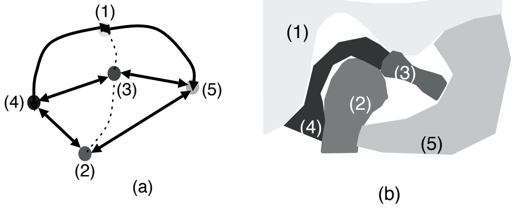

Figure 2: (a) Graph structure which represents the relations of external connectedness between the major parts of the TMJ, (b) TMJ with articular disc not positioned between condyle and temporal bone.

We define the following constant mereotopological relations: Object x is a *constant* part of object y if and only if whenever y exists, x is a part of y. Object x is a *constant proper part* of object y if and only if whenever y exists, x is a proper part of y. Object x is a *constantly* connected to object y if and only if whenever y exists, x is connected to y. Object x is a *constantly* externally connected to object y if and only if whenever y exists, x is externally connected to y. Object x is a *constantly* disconnected from object y if and only if whenever y exists, x is disconnected to y.

Consider Figure 2 (a). Every part of the TMJs in Figure 1 (a) and (b) is topologically equivalent to a filled circle which is indicated by the corresponding labels of the dots in Figure 2. Moreover, the nodes (the labeled circles) in the graph represent constant proper parts of the TMJ: at all times at which the TMJ as a whole exists, the condyle (2) is a proper part of it. Similarly the temporal bone (1), the articular disc (3), the posterior attachment (4), and the lateral pterygoid muscle (5) are constant proper parts of the TMJ.

The solid edges in the graph in Figure 2(a) represent constant connectedness relations between parts of the TMJs depicted in Figure 1 (a) and (b): at all times at which the TMJ as a whole exists the condyle (2) is (externally) connected to the posterior attachment (4) and to the lateral pterygoid muscle (5). By contrast, a (with respect to time) different connectedness relation bolds between articular disc (3) and the temporal bone (1) and the articular disc and the head of the condyle (2): the disc is externally connected to different parts of the temporal bone and the head of the condyle at different times. In the graph in Figure 2(a) this is represented by dotted edges between the respective nodes.

ORDERING RELATIONS BETWEEN EXTENDED OBJECTS

Mereotopology alone is not powerful enough to sufficiently characterize the important properties of TMJs. Consider the graph in Figure 2(a), which is a graph-theoretical representation of the mereotopological properties of the TMJs depicted in Figures 1(a), 1(b), and 2(b). The fact that the TMJs depicted in the three figures have the same graph-theoretic representation shows that in terms of mereotopological properties we cannot distinguish the TMJs in Figures 1(a), 1(b), and 2(b).

Obviously it is critical to distinguish the TMJ in Figure 2(b) from the TMJs in Figures 1(a) and 1(b). It is the purpose of the articular disc in a TMJ to be *between* the condyle and temporal bone at all times. If we take the ordering relation of betweenness into account then the TMJs in Figures 1(a) and 1(b) can be distinguished from the clearly pathological TMJ in Figure 2(b) where the posterior attachment is between the condyle and the temporal bone and not the articular disc.

Ordering relations like betweenness describe the location of disjoint objects relatively to one other. Besides betweenness, ordering relations include: left-of, right-of, in-front-of, above, below, behind, etc. The science of anatomy has developed a whole set of ordering relation terms to describe the arrangement of anatomical parts in the human body: superior, inferior, anterior, posterior, lateral, medial, dorsal, ventral, rostral, proximal, distal, etc. The FMA, for example, has an 'orientation network' in which these kinds of relations are represented [23, 19].

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[2] Strictly speaking, this ability to slide is due to the fact that the articular disc is separated from the temporal bone by a film of fluid which fills the superior synovial cavity. As stated previously, for the purpose of this paper we will not consider cavities or holes, and so will consider that the articular disc is effectively free to slide to various positions along the surface of the temporal bone. Notice, however, that we could introduce a relation of adjacency. We would then have to distinguish between constant adjacency and temporary adjacency in the same way we distinguish constant external connectedness and temporary external connectedness.

Unfortunately, ordering relations between spatially extended objects are difficult to formalize. As [11] points out in her treatment of relation of betweenness: 'The problem with trying to characterize the betweeness relation on extended objects is that we typically use the betweeness relation only on objects that have fairly uniform shapes and are nearly the same size. It is unclear whether or not the betweeness relation should hold in certain cases involving irregularly shaped objects and differently sized objects.' Similar problems face attempts to formalize qualitative direction relations between spatially extended objects, e.g., [20]. Similarly it is very difficult to qualitatively describe distances between extended objects particularly if they are of different size and shape, e.g., [37, 36].

LANDMARKS

To avoid problems that occur when describing ordering relations between extended objects we will choose a different approach: we will characterize shape, extent, and spatial arrangement of anatomical structures and their anatomical parts using (point-like) *anatomical landmarks* [6] and qualitative ordering relations between the landmarks.

Landmarks of anatomical structures

Intuitively, anatomical landmarks are *special salient points* on the surface of anatomical structures or their anatomical parts [6]. Consider the temporal bone in Figure 3. Salient points on the inferior surface of the temporal bone are local minima (LM3, LM7), local maxima (LM1, LM5) as well as points at which changes from convexity to concavity occur (LM2, LM4, LM6).

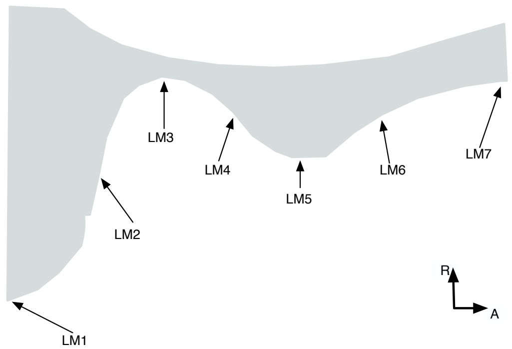

Figure 3: Landmarks on Joe's temporal bone.

However not all salient points on the surface of a given anatomical structure are landmarks. Salient points are landmarks of anatomical structures *of a given kind* if and only if:

1. They exist as parts of every anatomical structure of that kind;
2. They are critical for the normal function of all anatomical structures of that kind.

Thus the salient points LM1-LM6 in Figure 3 are anatomical landmarks of temporal bones of normal human TMJs, since (a) they exist as parts of every temporal bones of a normal human TMJ and (b) they are important for the function of a human TMJ as a whole. Consequently, independently of the normal variations between the actual shape of temporal bones in different human beings, all normal temporal bones will have the landmarks LM1-LM7 as depicted in Figure 3.

Qualitative distances between landmarks

Although normal temporal bones in human TMJs will have the landmarks LM1-LM7, the particular metric properties like the actual height of the maximum, the actual depth of the minimum, as well as their actual distance, will vary from individual to individual.

Consider the landmarks of the temporal bone depicted in Figure 3. Rather than quantitatively characterizing shape differences in terms of coordinate differences among the landmarks, we can characterize the shape differences qualitatively by specifying *qualitative* distance relations between those landmarks. Consider, for example, the anatomical landmarks LM1 and LM3. In Figure 3 the coordinate difference along the anterior (horizontal) axis is smaller than the coordinate difference along the rostral (vertical) axis. Similarly the coordinate difference between LM3 and LM5 along the anterior axis is roughly twice as large as the coordinate difference along the rostral axis.

Since all TMJs will have the same landmarks on their temporal bones (assuming a certain degree of anatomical normality), we can classify TMJs according to qualitative coordinate differences between their landmarks. There are many ways of doing this. Here we only discuss some examples to demonstrate the power of the qualitative methodology. In particular we focus on the landmarks LM1, LM3, and LM5.

Given a coordinate system[3] existing coordinate

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[3] We do not need the coordinate system for measurement. We only use it to distinguish coordinate differences in anterior (horizontal) direction (δh) from coordinate differences in rostral (vertical) direction (δv).

differences between LM1 and LM3 along the anterior axis (δa^1_3) and along the rostral axis (δr^1_3) can be used to distinguish the following cases: $\delta a^1_3 = \delta r^1_3$, $\delta a^1_3 < \delta r^1_3$, and $\delta a^1_3 > \delta r^1_3$. Here $\delta a^1_3 = \delta r^1_3$ means that δa^1_3 is as large as δr^1_3, $\delta a^1_3 < \delta r^1_3$ means that δa^1_3 is smaller than δr^1_3, and $\delta a^1_3 > \delta r^1_3$ means that δa^1_3 is larger than δr^1_3. Notice that this classification is *jointly exhaustive and pairwise disjoint*. That is, for any possible constellation of the anatomical landmarks LM1 and LM3 exactly one of those relations holds. In Figure 3 the rostral coordinate difference between LM1 and LM3 is larger than the anterior coordinate difference between LM1 and LM3, i.e., $\delta a^1_3 < \delta r^1_3$.

Of course we can in addition classify the anterior and rostral coordinate differences between the landmarks LM3 and LM5 in the same way. If we take both classifications together then the following nine combinations are combinatorially possible:

$R \in \{=,<,>\}$	1	2	3	4	5	6	7	8	9
$\delta a^1_3 \; R \; \delta r^1_3$	$=$	$=$	$=$	$<$	$<$	$<$	$>$	$>$	$>$
$\delta a^3_5 \; R \; \delta r^3_5$	$<$	$>$	$=$	$<$	$>$	$=$	$<$	$>$	$=$

Any possible constellation of LM1, LM2, and LM3 is characterized by exactly one column in this table. In Figure 3 we have $\delta a^1_3 < \delta r^1_3$ and $\delta a^3_5 > \delta r^3_5$. which corresponds to column 5 in the above table. Since this classification is exhaustive we now can analyze which of the nine possibilities are normal and which are pathological or which correlate with certain clinical symptoms. This analysis may show that distinguishing nine cases is insufficient to make the necessary distinction to distinguish normal anatomy form various kinds of pathologies. In this case we have three options: (a) take more landmarks into account; (b) distinguish more relations; (c) do both (a) and (b).

Consider option (b) instead of distinguishing three relations $=$, $<$, and $>$ we could add two more relations: $\ll$ and $\gg$ interpreted as much smaller and much bigger respectively. Another way of distinguishing more relations would be to refine $>$ by distinguishing twice as big, three times as big, etc. There are no limits to this method provided the resulting set of relations is jointly exhaustive and pairwise disjoint.

Notice that it might be more realistic to replace the identity relation $=$ by the relation $\sim$, were $\delta a \sim \delta r$ means that δa is *roughly* as large as δr. The exact definitions of the relations $\sim$, $\ll$, and $\gg$ are not trivial and their formalization is beyond the scope of this paper. For discussions of existing approaches see [21, 9, 7, 4].

Qualitative directions and orientation relations between landmarks

There exist a variety of approaches to qualitatively represent angles between landmarks and to use landmarks as origins for qualitative frames of references. For example, the landmark 'LM' in Figure 4(a) could serve as the origin of the qualitative frame of reference in Figure 4(b). We then could specify the location of anatomical landmarks of the heart within this frame of reference.

Most of the approaches to qualitative orientation and directions also incorporate qualitative distance relations like close, near, far, etc. (where close, near, and far roughly correspond to the relations $\sim$, $<$, and $\ll$ – see for example, [7, 4] for details). In Figure 4 we then could say that all anatomical landmarks of the heart are near and in front with respect to the frame of reference which is centered at the landmark LM. More sophisticated ways of representing qualitative order relations between landmarks were proposed in [15, 25, 26].

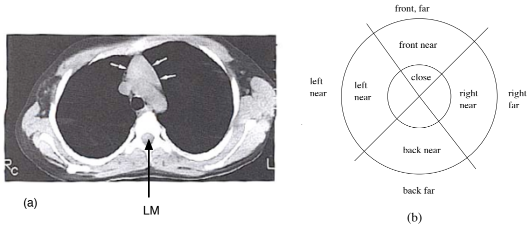
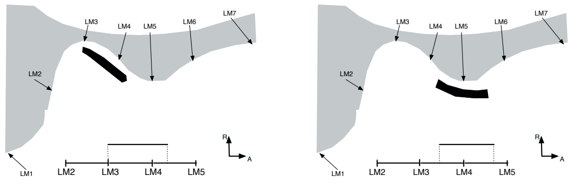


Figure 4: (a) a radiographic section taken through a human thorax. Arrows point to the heart. LM, Is a point in the center of the spinal cord. (b) qualitative ordering and qualitative distance relations according to Hernandez [17].

APPROXIMATE LOCATION IN FRAMES OF REFERENCE

There are many ways to represent approximate location in qualitative frames of references. (See, for example [3].) Here we discuss a specific technique which is useful in the context of our TMJ example. Consider the boundary of Joe's temporal bone as depicted in Figure 3. Topologically, the boundary is a one-dimensional curve. Since the landmarks LM1-LM7 are points on this curve, each landmark is a boundary of at least one interval (a one-piece part of the underlying curve). For example, in Figure 3 the landmarks LM2 and LM3 bound the interval which is formed by the part of the curve between them. We use the landmarks that bound a given interval to refer to this interval. For example, we write $\overline{\mathrm{L2L3}}$ to refer to the interval bounded by LM2 and LM3 in Figure 3.

In our mereotopological framework we can represent the topological relations between the intervals formed by the anatomical landmarks of Joe's temporal bone as: Interval $\overline{\mathrm{L1L2}}$ is constantly externally connected to interval $\overline{\mathrm{L2L3}}$, interval $\overline{\mathrm{L2L3}}$ is constantly externally connected to interval $\overline{\mathrm{L3L4}}$, and so on.



(a) (b)

Figure 5: Relations between articular disc and landmark intervals of the temporal bone at times t_1 (a) and t_2 (b).

Consider Figures 5(a) and (b) which depict the relative location of Joe's articular disc with respect to his temporal bone at times t_1 and t_2 respectively. Figure 5(a) corresponds to Figure 1(a) and both show Joe's TMJ in the jaw closed position. Similarly, Figure 5(b) corresponds to Figure 1(b) and both show Joe's TMJ in the jaw open position. On the bottom of both images in Figure 5 the projection of Joe's articular disc onto the boundary of his temporal bone is depicted. From this point on, we will write $\mathit{Prj}(D, t)$ to refer the interval that is the projection of Joe's articular disc on the boundary of his temporal bone in a sagittal section through the middle of his condyle at time t.

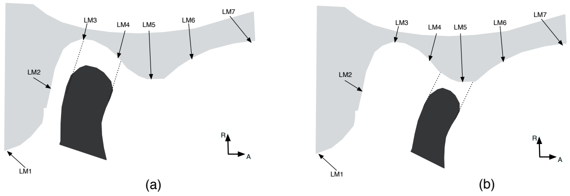
The interval $\mathit{Prj}(D, t)$ stands in mereotopological relationships to the intervals bounded by the landmarks LM1-LM7. For example, at time t_1 the projection of Joe's articular disc completely covers the interval $\overline{\mathrm{L3L4}}$, i.e., $COV(Prj(D, t_1), \overline{\mathrm{L3L4}}, t_1)$. In other words the interval $\overline{\mathrm{L3L4}}$ is a part of the projection of Joe's articular disc, i.e., $\mathit{PartOf}(\overline{\mathrm{L3L4}}, \mathit{Prj}(D, t_1), t_1)$. Notice that at time t_2 the projection of Joe's articular disc and the interval $\overline{\mathrm{L3L4}}$ are disconnected, i.e., $DC(\overline{\mathrm{L3L4}}, \mathit{Prj}(D, t_2), t_2)$.[4]

Thus at every time t we can specify the location of Joe's articular disc with respect to the landmarks of his temporal bone in terms of the relations which hold at time t between the projection of the articular disc at t and the intervals bounded by the landmarks. These mereotopological relations at time t_1 and t_2 can be summarized as:

Joe's disc	$\overline{\mathrm{L1L2}}$	$\overline{\mathrm{L2L3}}$	$\overline{\mathrm{L3L4}}$	$\overline{\mathrm{L4L5}}$	$\overline{\mathrm{L5L6}}$	$\overline{\mathrm{L6L7}}$
t_1	*DC*	*EC*	*COV*	*PO*	*DC*	*DC*
t_2	*DC*	*DC*	*DC*	*PO*	*PO*	*DC*

The first row reads as $DC(\mathit{Prj}(D, t_1), \overline{\mathrm{L1L2}}, t_1)$, $EC(\mathit{Prj}(D, t_1), \overline{\mathrm{L2L3}}, t_1)$, ...and similarly for the second row.

Consider the images shown in Figures 6(a) and (b) which depict the relative location of Joe's condyle with respect to his temporal bone at times t_1 and t_2 respectively. Figure 6(a) corresponds to Figure 1(a) and Figure 6(b) corresponds to Figure 1(b). In the same way we projected Joe's disc onto the boundary of his temporal bone to identify an interval that can be related to the intervals bounded by the landmarks LM1-LM7, we can project the head of his condyle onto the boundary of his temporal bone as indicated by the dotted lines in Figures 6 (a) and (b).



(a) (b)

Figure 6: Mereotopological relations between the head of the condyle and landmark intervals of the temporal bone at times t_1 (a) and t_2 (b).

As in the case of Joe's disc, at every time t we can specify the location of the head of Joe's condyle with respect to the landmarks of his temporal bone it terms of the relations which hold at time t between the projection the head of the condyle at t and the intervals bounded by the landmarks. The spatial relations at time t_1 and t_2 can be summarized as:

Joe's condyle	$\overline{\mathrm{L1L2}}$	$\overline{\mathrm{L2L3}}$	$\overline{\mathrm{L3L4}}$	$\overline{\mathrm{L4L5}}$	$\overline{\mathrm{L5L6}}$	$\overline{\mathrm{L6L7}}$
t_1	*DC*	*EC*	*PO*	*DC*	*DC*	*DC*
t_2	*DC*	*DC*	*DC*	*PO*	*PO*	*DC*

If we use C to denote the head of Joe's condyle then the first row reads as $DC(\mathit{Prj}(C, t_1), \overline{\mathrm{L1L2}}, t_1)$, $EC(\mathit{Prj}(C, t_1), \overline{\mathrm{L2L3}}, t_1)$, ..., and similarly for the second row. Notice that the table with the relations of Joe's articular disc corresponds nicely to the table with the relations of the head of Joe's

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[4] For details of the exact definitions of the relations between the intervals see [1, 2].

condyle, i.e., the articular disc is at both times *between* the head of the condyle and the temporal bone.

Clearly, for every possible location of an articular disc in a TMJ with respect to the temporal bone of this TMJ there is a unique sequence of relations similar to those in the table of Joe's disc. Similarly, for every possible location of the head of a condyle in a TMJ with respect to the temporal bone of this TMJ there is a unique sequence of relations similar to those in the table of Joe's condyle. Moreover, since we have, (i) the same anatomical landmarks on the temporal bones of every normal TMJ and, (ii) there are only a finite number of mereotopological relations that can hold between two intervals, we can therefore, compose two finite tables: one table in which each row corresponds to one anatomically possible location of some articular disc with respect to the corresponding temporal bone; a second table in which each row corresponds to one anatomically possible location of the head of some condyle with respect to the corresponding temporal bone.[5] Both tables together contain all possible combinations of locations of the head of a condyle and an articular disc with respect to the landmarks of a temporal bone in any possible TMJ. Some of these combinations we can classify as normal (among these are the two tables above) others are pathological and again others will be anatomically impossible and thus can be ruled out.

CONCLUSIONS

The purpose of this paper is to show that there can be obtained, by following the methodology we have presented here, a series of well understood qualitative formalisms which can be used to create a formal representation of canonical anatomy. This is accomplished by incorporating into the representation, using the qualitative methods of analysis we describe in this paper, information about, a) the mereological (parthood) relationships of anatomical structures, b) the topology (e.g., connectedness) of anatomical structures, and c) the shape of anatomical parts and the spatial arrangement of anatomical structures.

The five cornerstones of the proposed methodology are:

1. The grounding of the formalization of canonical anatomy in mereotopology (rather than mereology alone);
2. The strict distinction of time-dependent and time-independent relations;
3. The identification of anatomical landmarks for the representation of the shape of anatomical parts and the spatial arrangement of anatomical structures;
4. The identification of sets of jointly exhaustive and pairwise disjoint relations to describe relations between anatomical parts and anatomical landmarks;
5. The establishment of landmarks and qualitative distinctions that reflect the ontologically significant aspects of the canonical anatomy of biomedical structures as well as relevant pathological cases.

This methodology permits, in principle, the exhaustive qualitative characterization of all anatomically possible instantiations of anatomical structures. These then can be classified as normal or pathological and correlated with other clinical findings.

The discussion in this paper exclusively focused on relations between particulars (Joe Doe's TMJ). It is well known that anatomical ontologies are mostly about relations between universals or classes [32, 31]. However it is also well known that relations between universals or classes are defined in terms of relations between particulars [13].

Address for Correspondence

Thomas Bittner, State University of New York, Department of Philosophy, 135 Park Hall, Buffalo (NY), 14260, USA

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