An Anatomic Indexing System for Costal Cartilage and Its Application in Calcification Representation in Finite-Element Human Body Models

Y. Huang, Q. Zhou, SC. Wang, BB. Nie, SA. Holcombe

Abstract Costal cartilage plays an important role in the structural stiffness of the ribcage as segments that flexibly connect the bony ribs to the sternum. Calcification of costal cartilage occurring throughout adult life can substantially change local material properties and stiffen the structural mechanical response. Current finite-element (FE) human body models (HBMs) have a simplified representation of costal cartilage with homogeneous material properties, yet the FE meshes allow for discrete regions within a given mesh to be modeled using separate materials. To represent costal cartilage and its calcification across the population, this study proposed a consistent indexing system shared between HBMs as well as the real humans they represent. In this system, spatial positions in the costal cartilage are identified using a continuous coordinate space. This study also proposed a modeling framework to represent costal cartilage calcification in multiple models in a consistent fashion with real human data. This study successfully applied the indexing system to several current commercial FE HBMs and tested the ability of the framework with a limited set of real human data. The indexing system and modeling framework are expected to be a precursor to future study on the influence of calcification on mechanical responses of the ribcage.

Keywords age, anatomic indexing system, costal cartilage calcification, finite-element human body models, real human data.

I. INTRODUCTION

Costal cartilage flexibly bridges the space between the sternum and the bony ribs and plays an important role in the structural stiffness of the ribcage. In simulation studies, the overall chest stiffness increased by 50% with a tough shell added to the costal cartilage [1], the stress levels in the ribs increased by 63% with stiffened cartilage material [2] and the resulting risk of rib fractures in diagonal seatbelt loading also increased [3].

Costal cartilage is organized by a series of segments composed of hyaline cartilage mid-substance and an outer layer of perichondrium. Calcification or ossification of the costal cartilage takes place throughout adult life and produces inhomogeneity of cartilage mid-substance with substantial change in the local material properties. The effects of calcification on effective material behavior can substantially stiffen the mechanical response of the cartilage, and this effect is highly dependent on the microstructural connectivity [4-5]. In general, cartilage calcifies or ossifies as discrete regions within and between costal segments, as opposed to accumulating diffusely throughout the cartilage material itself. In individuals with dense calcification, ossified cartilage from multiple regions join to connect across the full costal segment. There are distinct categories of calcification found in analysis of microCT with respect to location, microstructure and shape, for instance, region shapes of rods and plates are most prevalent at the periphery [6]. As these regions grow to the order of millimeters in length, they can also be seen on medical X-Ray [7] and CT imaging [8-9]. Magnitude of costal cartilage calcification has shown significant trends with age, and differences in typical patterns of calcification distribution and growing have been observed between males and females [9-16].

Computational human body models are widely used to study the biomechanics of the thorax to loading. Current finite-element (FE) human body models (HBMs) have a simplified representation of costal cartilage via a network of finite elements with homogeneous material properties [17-19], while the addition of calcification has not been explored. As current commercial FE models contain costal cartilage elements with edge lengths of 5-10

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mm, the discretized nature of FE meshes also allows for discrete regions within a given mesh to be modeled using separate materials. Such a modeling technique has been successfully applied to individually-meshed isolated cartilage segments with nominal element sizes of 1.5 mm [5,20]. However, it has not been applied to current commercial FE HBMs to represent either a specific subject or a target population. This is partly due to limitations in available data that details calcification either from individuals or population groups. However, another obstacle comes from the geometric complexity of the costal cartilage itself, whereby an individual subject's network of cartilage segments is not easy to be registered with another subject or indeed with available data sources. In order to represent costal cartilage and its calcification in a general form when both vary considerably across the population, it is desirable to have a consistent indexing system shared between HBMs as well as the real humans they represent.

The objective of this research is to develop an anatomic indexing system for costal cartilage and apply it in the representation of costal cartilage calcification in FE HBMs with real human data. In this system, spatial positions in the costal cartilage can be identified using a continuous coordinate space. With this system, regions of calcification that are identified via sources such as medical images could be systematically transferred to the corresponding anatomic regions within HBMs. With numerous FE models in use throughout the impact biomechanics field and large amount of raw data from real subjects, there is value in laying out a framework to reflect population diversity during FE modeling. In this study we will also develop such a framework and test it – along with the anatomic indexing system. A limited set of real human data will be used to demonstrate the ability of the framework to apply such data to four current commercial FE HBMs in a consistent fashion with the anatomic indexing system and statistical tools.

II. METHODS

Overall Methodology and Approach

In the current study, the overall approach (Fig. 1) begins with the development of a systematic indexing system that can unambiguously define the physical positions within a costal cartilage network. Nodes in FE HBMs and voxels in CT images can be indexed in this consistent system. A statistical tool was next developed with data from real subjects, that could take any specific coordinate indexed in the anatomic system and the age and sex of the subject as inputs, then provide the volume ratio of calcification of the segment it belongs to and its calcification probability – i.e., the likelihood that the cartilage tissue at the point in question has become ossified. Finally, a scheme for applying that statistical models to HBMs was developed that (1) takes the HBM model itself as input, (2) passes the coordinates of all nodes within the FE mesh to the statistical tool to obtain their calcification probability, and transforms those nodal probabilities into decisions on whether each specific element within the mesh should be categorized as regular or calcified cartilage, and then (3) creates a new keyword file of costal cartilage with calcified and uncalcified tissues modeled using a mixed material matrix.

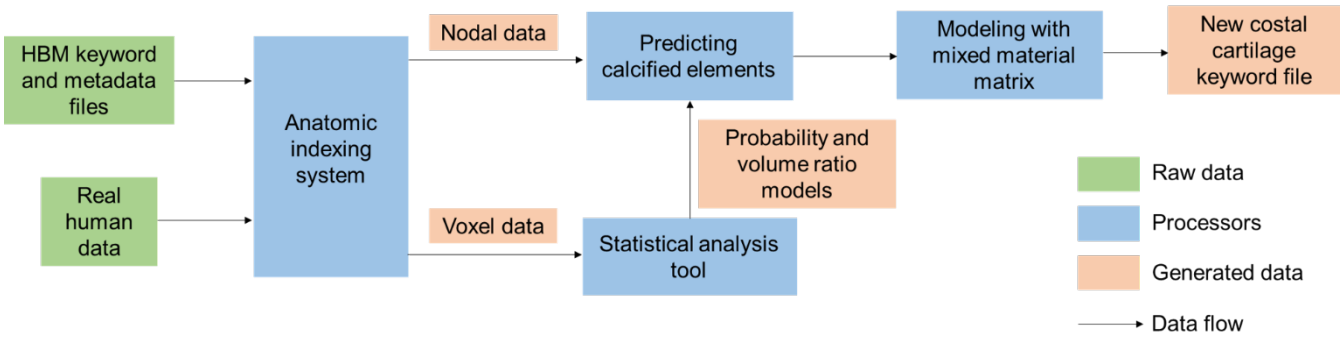


Fig. 1. Workflow of modeling calcified costal cartilage in FE HBMs with real human data

Each of these steps are described below in more details, but this study focuses primarily on the indexing system and the final application to currently available FE models. An initial statistical tool for predicting calcification volume ratio and probability from live subject data is also described below. However, this tool is limited in the subject pool from which it is sourced and is not intended as a data source for quantifying general patterns and amounts of calcification in wider populations. Instead, it is only included here to facilitate understanding of an

overall system design for incorporating cartilage calcification knowledge into HBMs.

An Anatomic Indexing System for Costal Cartilage

To spatially index a given costal cartilage network, the network was first discretized into two categories of cartilage segments. Firstly, rib segments are those that connect directly to ribs via costochondral joints and generally span to meet the sternum at sternochondral joints, and secondly, bridging segments are those that connect to other cartilage segments on both sides via interchondral joints (Fig. 2a). These are each treated as separate cartilage segments, and spatial positions within each segment were then identified using a continuous coordinate space.

Within any given cartilage segment a central curve is set up that runs along its core. For a rib segment, this central curve stretches from the rib end to the sternal end. At any point along this continuous curve, a local coordinate system can be made (Fig. 2a) with three vectors pointing in anatomically relevant directions. The first of these simply points along the tangent direction of the central curve, giving a local rib-towards-sternum direction vector (*Vr2s*). A second vector, *Vs*, gives a local body-superior direction. It is specified by the average direction towards the nearest point on the center line of the superior/inferior rib segments, rectified so as to remain perpendicular to *Vr2s*. Finally, a locally anterior direction, *Va*, can be defined via the cross-product of *Vs* and *Vr2s*.

For any position (*P*) within the whole of the rib segment (not just along its central curve), the foot of perpendicular (*O*) on the center line was calculated (Fig. 2b). The normalized distance from the rib to *O* along the center line was defined as the position along the segment (*DistFromRib*) for *P*. By interpolation and orthogonalization, the local coordinate system for *O* was figured out. By translating the plane defined by *Vs* and *Va* in the local coordinate system of *O* to pass through *P*, the cross section defined by *Vs'* and *Va'* through *P* was defined (Fig. 2c). In the cross section, the normalized position ranging from the core to the cortex (*DistFromCore*) and the rotational position relative to the cross-sectional center (*AngleWithVa*) in the polar coordinate defined by *Va* were identified.

For a bridging segment, the center line stretching from the upper interface to the lower interface with rib segments was also fitted along its core, and the local coordinate systems for points at both ends were defined referring to the superior and inferior rib segments. Then, with the same calculation process for positions in rib segments, for each spatial position in the bridging segment, its normalized distance from the upper interface with the rib segment (*DistFromUp*, which corresponds to *DistFromRib* in rib segments), *DistFromCore* and *AngleWithVa* were identified.

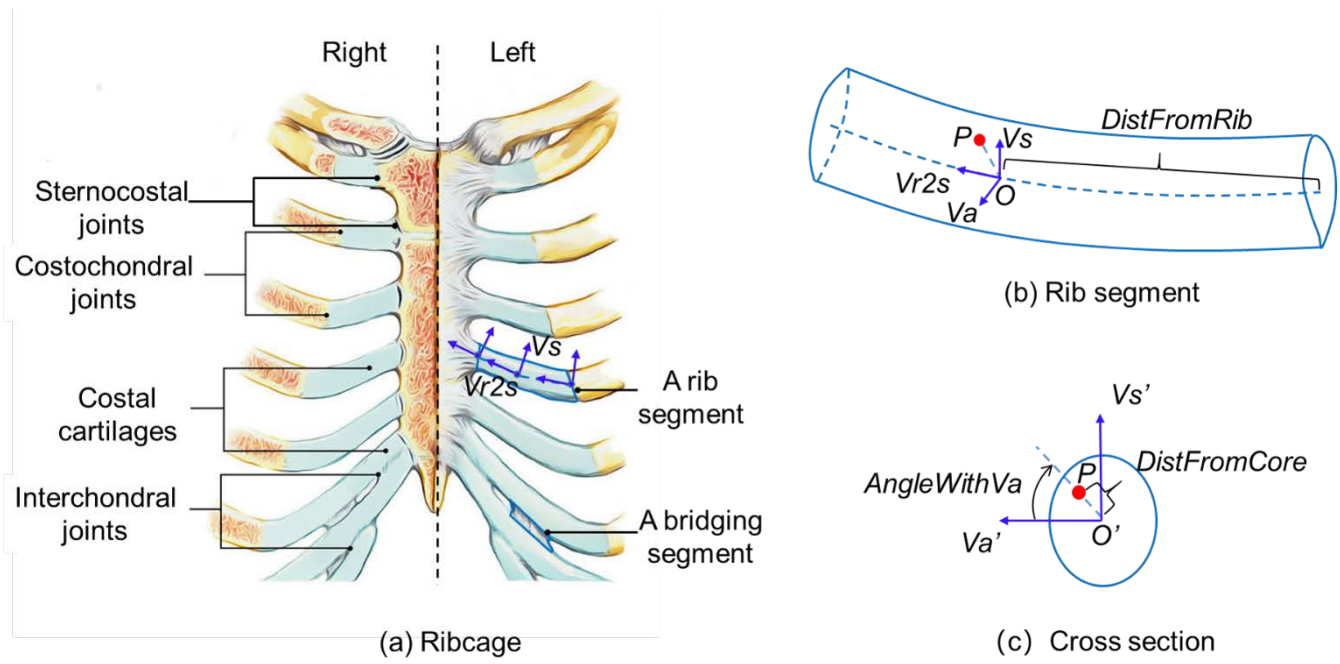


Fig. 2. An anatomic indexing system having (a) discretized costal cartilage separated into rib segments and bridging segments with fitted center lines and perpendicular local direction to the superior costal neighbor (*Vs*); (b) and (c) full segment coordinate system of *DistFromRib* (curve-linear position along the centerline), *DistFromCore* (location within

a segment cross section from the core to the cortex), and *AngleWithVa* (rotational position with respect to the body anterior direction (*Va*)).

Statistical Models for Predicting Calcification Amount and Pattern

With the aim of developing a tool for predicting the likelihood of calcification at a given site within the cartilage network, 28 individuals (13 females, 15 males) aged from 6 to 90 years collected from the International Center for Automotive Medicine (ICAM) morphomics database were identified (Fig. 3). Within each subject the anatomic indexing system was realized by laying out the network of 3D curves (representing cartilage segment cores) and 3D surfaces (representing cartilage segment cortices). All image voxels falling within the segment boundaries were anatomically indexed and collected with a categorization of regular cartilage tissue (under 160 CT Hounsfield Units, HU) and calcified cartilage tissue (above 160 HU). With the new sets of metadata relating to the voxels in the costal cartilage, the volume ratio of calcification in each segment was achieved by dividing the accumulated volume of voxels categorized as being calcified by the total volume of voxels in the segment.

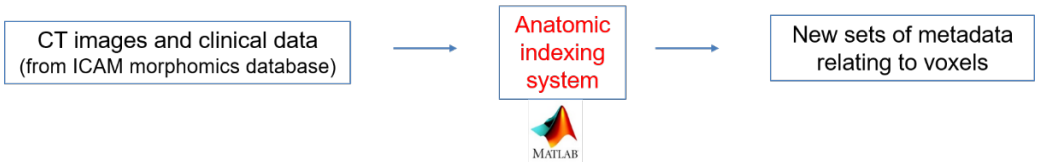


Fig. 3. The sketch of processing real human data within the indexing system.

Then a generalized regression model (referred as 'VolRatioModel') was developed to predict the volume ratio of calcification in each segment with sex, age and segment number as predictors (Fig. 4). To predict the probability to be calcified of each position, a bootstrap-aggregated decision tree classifier (referred as 'ProbModel') was developed with sex, segment number (SegNo) and anatomic position indexes as predictors (Fig. 4). Age was included in VolRatioModel but not included in ProbModel, this was due to the fact that initial models showed that age affected the overall volume of calcification (and therefore the amount of calcified positions increased with age as a whole), but the representative calcification pattern on the scale of age among the population only existed significant difference between the sexes, that is the sequential order of positions to be calcified determined by their relative magnitudes of probabilities in a segment is immutable as aging.

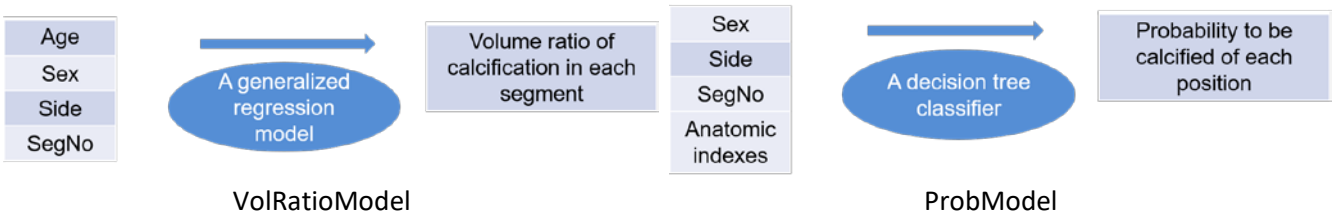


Fig. 4. The sketch of two statistical models developed with real human data.

Indexing the Nodes in the Costal Cartilage of FE HBMs

A custom MATLAB program was written to realize the anatomic indexing system and its application to FE HBMs, which takes the HBM keyword file as input along with a metadata file unique to each model (Fig. 5). The metadata file defining the IDs of elements in bridging segments was created with LS-PrePost. In the program for indexing, the data in node cards and element cards related to the costal cartilage were extracted from the keyword file automatically. Along with the element IDs in bridging segments supplied in the metadata, by detecting the connectivity of nodes by the referential relations between nodes and elements, the nodes were separated into the segments they belonged to. In the discretized rib and bridging segments, with the help of the connectivity between nodes and raw spatial coordinates of nodes, the nodal positions were identified in the anatomic indexing system.

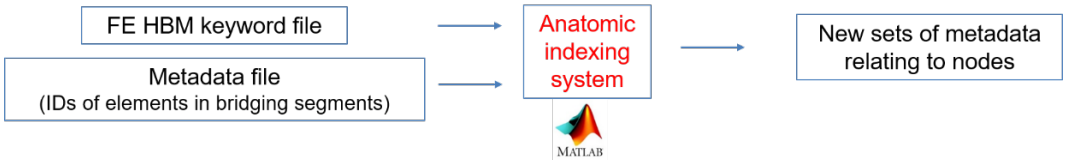


Fig. 5. The sketch of processing FE HBMs within the indexing system.

Predicting Calcified Elements in FE HBMs

Another custom MATLAB program was written to represent the costal cartilage calcification of a person of certain sex and age in a FE HBM. The calcification volume ratio of each segment and the calcification probability of the indexed nodes were predicted with the developed statistical models (VolRatioModel and ProbModel). The calcification probability of each element (solid/shell) was achieved by averaging the probabilities of the nodes it referred to, and the elements in the same segment were sorted in a descending order of their calcification probabilities. The network of costal cartilage consists of a bunch of solid elements covered by a layer of shell elements in these four FE HBMs, except in GHBMC F05, where only solid elements are used. The thicknesses of the shell elements were assumed to be uniformly 0.5 mm in this study, then the volume of each shell and solid element were calculated. In each segment, the ordered elements contributed to the cumulative volume ratio closest to the predicted calcification volume ratio of this segment were labeled as being calcified.

Representing Cartilage Calcification Using a Mixed Material Matrix

As the material property of a given element is defined by the material card assigned to the part it belongs to, the countermeasure of using a mixed material matrix by distributing the elements in the costal cartilage into parts with material properties of calcified/un-calcified costal cartilage was taken. With the IDs of elements labeled as being calcified, a new keyword file defining all the cards relating to the costal cartilage was created with the calcified elements being assigned to new parts. The card IDs, section properties and material properties were left to be user-defined on the user interface of the program.

III. RESULTS

The indexing methodology was successfully applied to GHBMC M50 and F05 (Version 4.5) and THUMS M50 and F05 (Version 4.0) in the custom MATLAB program for indexing. The program is robust enough to automatically process these four models. The outputs are corresponding new sets of metadata relating to each node within the costal cartilage that specifies its spatial anatomic indexes (Fig. 6). In the perspective of morphology, the bridging segments in THUMS models are not represented in meshes, i.e. the rib segments are connected by sharing nodes instead of bridging segments, so the *DistFromUp* for nodes in bridging segments were not calculated for THUMS M50 and THUMS F05 as shown in Fig. 6.

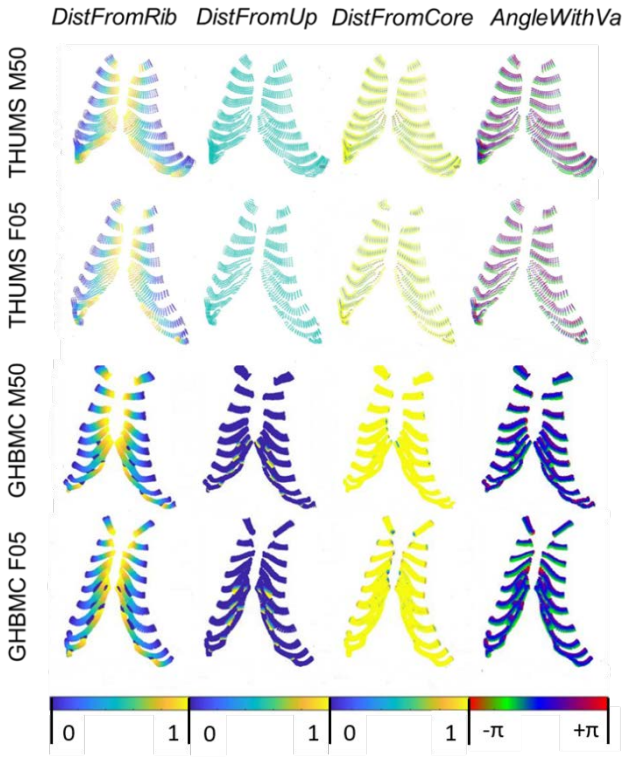
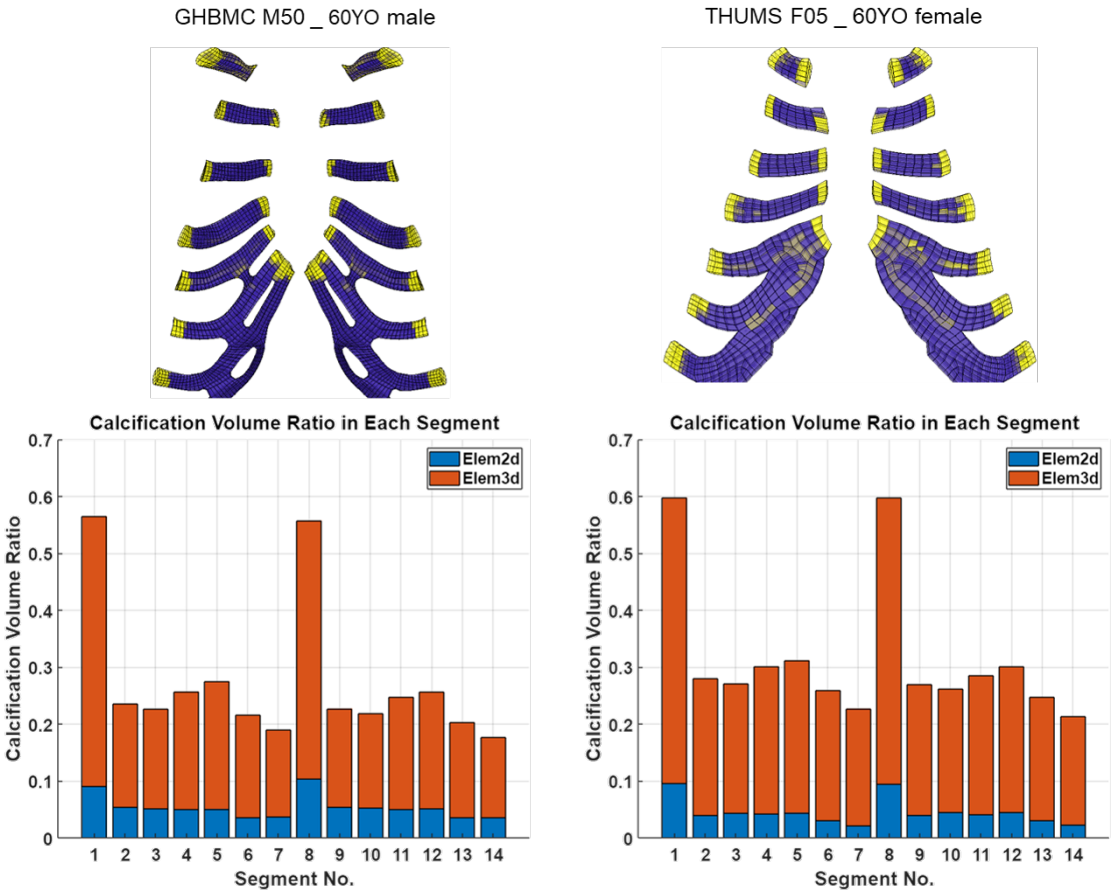


Fig. 6. The illustration of anatomic indexes of nodes (the normalized distance from the rib or the bridging upper interface, the normalized distance from the core and the angle with the vector pointing to the anterior) in the costal cartilage of THUMS M50, THUMS F05, GHBMC M50 and GHBMC F05.

With our ongoing work on processing and identification of medical images, the rib segments that connected the upper seven ribs to the sternum of the 28 subjects were successfully indexed and input into the statistical tool. Due to the limited sample size and the relatively simplistic delineation between costal cartilage and rib/sternum, the confidence coefficient of current statistical models is not satisfying, but they are acceptable as trials for the demonstration of the modeling framework. For a person of certain sex and age, the custom MATLAB program successfully predicted the calcification volume ratio in each segment and realized the identification of elements to be calcified or not. Fig. 7 shows the prediction results for a male and a female both with age of 60 years and their representation in GHBMC M50 and THUMS F05 respectively as examples. The volume ratios of calcified 2D elements and calcified 3D elements in each segment were also calculated and shown in stacked bar charts in Fig. 7. With the access to define the material and section properties, the new keyword files relating to the costal cartilage extracted from the user interface of this program (Fig. 8) can be loaded in pre-processing software for LS-DYNA and enable the simulation study on the influence of calcification on mechanics in next steps.



(a) (b)

Fig. 7. Examples of representation of costal cartilage calcification in FE HBMs： (a) represent a 60-years-old male in GHBMC M50; (b) represent a 60-years-old female in THUMS F05. Top row: labelling the elements to be calcified (in yellow); Bottom row: calculating the volume ratios of calcified solid elements (Elem3d) and calcified shell elements (Elem2d) (from the left to the right, from the superior to the inferior, the rib segments connecting the upper seven ribs to the sternum were numbered from 1 to 14).

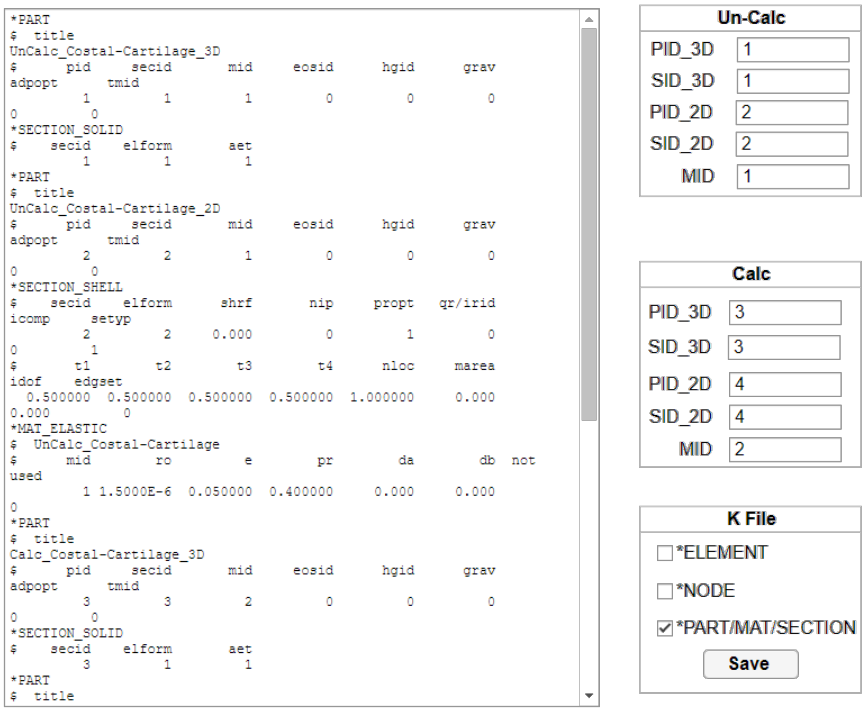


Fig. 8. The interface to define the output of a keyword file of the calcified costal cartilage with the access to

modify the numbering of card IDs, section properties and material properties.

IV. Discussion

This study developed an anatomic indexing system for human costal cartilage for application to both FE HBMs and clinical images. With this system, regions of calcification that are identified via sources such as medical images could be systematically transferred to the corresponding anatomic regions within HBMs. The focus has been on the methodology through which real subject data may be transferred to HBMs, with the intention that future work introducing calcification into multiple HBMs will do so in a generalized and consistent fashion, regardless of the specific target model.

Relevance to Previous Work

Previously, Forman and Kent [20] built finite element component models of the costal cartilage and modeled regions of calcification derived from CT images of cadaveric specimens. They found that the biofidelity of mechanical behavior of their models with calcified elements was superior to those without. Their models were necessarily personalized models, limited to the specific specimens harvested. In order to transfer one of their modeled costal segments into a full HBM, 3D registration of each individual segment onto the target HBM segment would be required. This process would need to be repeated if those same segments were to be transferred into a different HBM. With the indexing system developed in this study, the cartilage coordinate scheme need only be laid out once across a given segment, and its transfer could be performed into multiple FE models. Furthermore, the transfer of data from a single subject (i.e., a subject-specific model) into FE HBMs would follow the same general workflow as the transfer from a statistical aggregation that represents average calcification from a chosen subject population.

Using Two Separate Models as the Statistical Tool

Within our methodology we have chosen to implement two separate statistical models: firstly, we predict the total volume of calcification within a given segment; secondly, we predict the probability (for each node within a mesh) of that node lying within a calcified region. It would be entirely possible to only utilize this second prediction by applying a standard threshold (categorizing nodes as calcified if, for example, their calcification probability reached 50%). The drawback of that approach is that a specific probability threshold to be chosen may differ for different mesh densities, since there would be no guarantee that with the selected threshold, the elements within the target HBM labeled as being calcified would produce an appropriate amount of calcified tissue equal to that of the subject it represents. Instead, we only utilize the second prediction (of nodal calcification probability) to rank the nodes in terms of calcification likelihood, and then use the first prediction of target calcification volume to set a threshold up to which we consider a node as being calcified. It should be noted that nodes themselves do not hold an intrinsic volume so they alone cannot be used to specify a target volume of calcification. Instead, we chose to let elements within the mesh adopt their average nodal calcification probability, and therefore those elements are incrementally categorized as being calcified until the desired calcification volume is reached. This choice means that consideration should be given to the network structure consisting of nodes and elements of the costal cartilage within a given HBM.

In-depth analysis and validation of statistical results were not conducted in this paper, firstly subjecting to the limited sample size and the relatively simplistic delineation between costal cartilage and rib/sternum in image processing. Secondly, as the main focus of this paper is on an anatomic indexing system and modeling framework for calcified costal cartilage, the rough statistical models are acceptable as trials for the demonstration of the modeling framework. In next steps, we need more work on imaging processing and statistical analysis with more real human data. In future statistical analysis, validation should involve taking specific individuals (with a known age and sex) and then comparing the calcification that is predicted by these population models (both in volume and spatial distribution) to the specific volume and distribution actually observed in those individuals. Beyond just a visual comparison of these two distributions, metrics for validation could include the overall volume of calcification as well as spatial comparison tools such as Dice similarity coefficients (DSC). And to improve model confidence level, more morphomics (e.g. height, BMI) and coupling terms can be included to determine the

appropriate predictors.

Combinations of Shells and Solids, and Material Properties

In modeling calcification, it is important to consider the actual morphology of calcification in human subjects as well as the available geometry and mesh within target HBMs. Measurements of costal cartilage calcification volumes and distribution have shown significant trends with age, and the different morphologies of accumulated calcified cartilage between male and female were observed across the population [9-16]. Specifically, males are reported to exhibit a peripheral pattern (more calcification on the inferior and superior costal cartilage margin), whereas females show one or more central calcification patterns (pyramidal-shaped central tongues of calcification or centrally-placed smooth globules of calcification) (Fig. 9). In these four FE HBMs except GHBMC F05 adopted in this study, a layer of shell elements is attached to the solid elements originally to represent the perichondrium and the hyaline mid-substance, and the shell elements to represent the perichondrium are attributed MAT_NULL. As the thickness of calcification on the surface observed in real CT scans may be less than the edge length of solid elements in FE HBMs, the representation of a peripheral pattern only with solid elements may be unrealizable. The solution adopted in this study is treating both the core of solid elements and the surrounding layer of shell elements as mid-substance with the intention that rod/plate type configurations will be better represented using the shells than they would using the much larger (and differently shaped between different HBM) solid elements. As the examples shown in Fig.7, the volume ratio of calcified solid and shell elements can be used to quantitatively compare and identify the calcification pattern. In others where the shells do not exist (e.g. GHBMC F05), it is much easier to simply create them than it would be to remesh the solid region to introduce a “shell”-like zone around the periphery of segments. The borrowing of shell elements (originally exist to represent the perichondrium) does not mean that the influence of perichondrium on structural mechanical responses will be ignored in future simulations, the duplication of the surrounding layer of shells can be conducted for representation.

The mixed material matrix realized the modeling of heterogeneity of materials in costal cartilage with calcification. In this paper, we’re not paying efforts to calibrate material models for the costal cartilage, but the access to define the material cards in the new keyword file was left to be user-defined. In current program, we are using current literature sources as placeholders for generic “calcified” and “uncalcified” cartilage material properties in the creation of new keyword files, i.e. a template with two different material cards (Fig. 8). Valid material properties need to be attributed later in simulations for biomechanical studies.

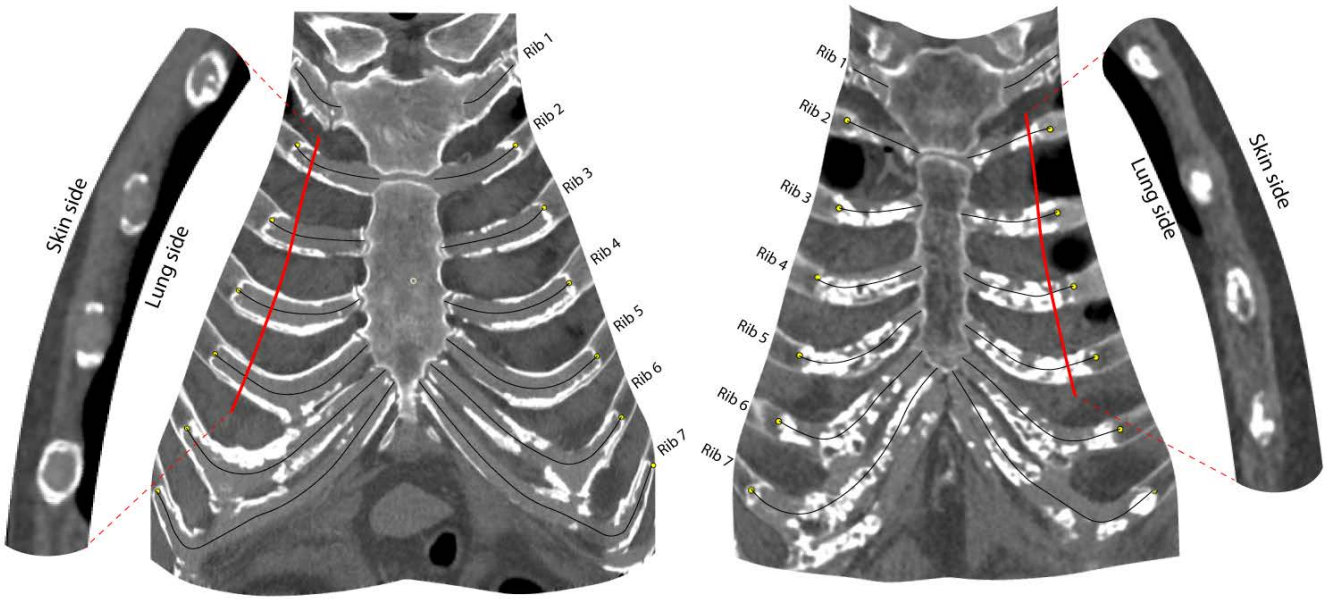


Fig. 9. Exemplar male (left) and female (right) cartilage calcification morphology. Males tend to accumulate a peripheral pattern of calcified rods and plates, whereas females tend to accumulate calcification in nodules emanating from nearer to the core of the cartilage segment.

Appropriateness of Current HBM Meshes

Regarding to the biofidelity of the four commercial FE HBMs adopted in this study, by comparing the costal cartilage between the HBMs' meshes and the real subject anatomy (Fig. 10), it was found that GHBMC models have a more biofidelic morphology with distinct bridging segments, which is preferable for representing cartilage calcification in bridging segments. With respect to the location of sternocostal joints on the sternum, GHBMC F05 exhibits relatively weak biofidelity, as the second sternocostal joint (connecting the second rib segment to the sternum) should adjoint the sternal angle instead of connecting on the manubrium (Fig. 10).

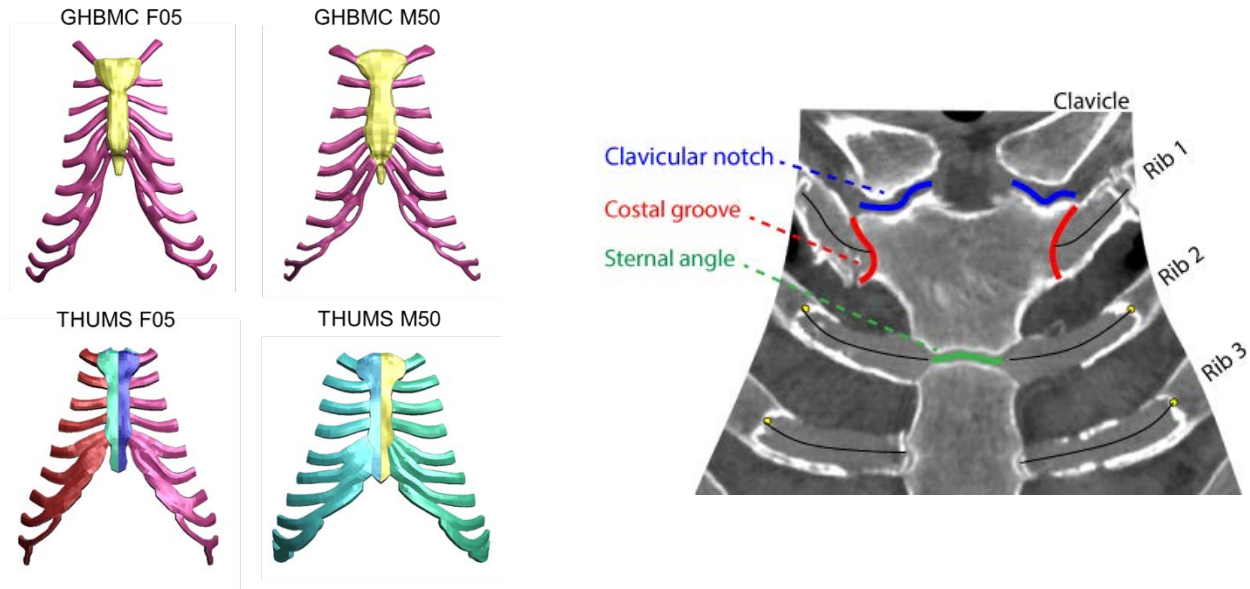


Fig. 10. Morphology of costal cartilage in FE HBMs and real subjects. The GHBMC models contain a more realistic depiction of bridging segments between lower cartilage segments, however upper segments in the GHBMC F05 show atypical morphology in their connections to the sternum.

Precursor to Future Study

The created keyword file defining a calcified costal cartilage FE model in this study along with later valid user-defined material properties can be incorporated into biomechanical models to better understand how calcifications in the aging thorax will affect the structural mechanical response of the rib cage. In microstructural studies, multiple different structured morphologies of calcifications in the costal cartilage have been observed, including a complex structure similar to a cross-section of diaphysial bone, with a dense shell surrounding a trabecular core [6]. In micromechanical studies, Lau [4] simulated the effective elastic modulus of heterogeneous cartilage segments with highly connected or floating calcifications using the generalized method of cells and explored the effects of microstructural connectivity of the calcification on the effective material behavior of the cartilage. Results showed that the stiffness increases substantially as calcification connectivity increases, suggesting that both the connectivity and volume fraction of the calcification should be considered when modeling calcifying cartilage in FE models. Forman and Kent [5,17] set the distinct solid finite elements corresponding to regions of calcification (as derived from CT images of the cadaveric specimens being modelled) to a stiffer material property in the developed subject-specific finite element component models of the costal cartilage, and further studied the sensitivity of the structural force–displacement responses to the magnitude of the calcified regions within the cartilage, whereby progressively larger (or smaller) clusters of elements were assigned the calcification material model. With the programs developed in this study, once the valid statistical models and material models are achieved in next steps, computational models of costal cartilages with calcifications that can reflect the population diversity in the real world can be created efficiently, subsequent simulation analysis on the mechanical responses can be conducted considering the aging effects and sexual difference.

V. CONCLUSIONS

This study proposed an anatomic indexing system to identify the spatial positions in a continuous coordinate space within the costal cartilage, and successfully applied it to several current FE HBMs. With the statistical models from real medical data processed with the same indexing system, a framework was developed to represent the calcified costal cartilage of a certain person with current FE HBMs and create new keyword files for future simulation studies on biomechanics. In the future, for the development of valid statistical models with real human data, we will refine the process of image processing and enrich the data pool. With the keyword file of calcified costal cartilage output from the framework proposed in this paper, we will study on the influence of calcification on mechanical responses on component and structure levels with FE simulations. And the FE HBMs representing costal cartilage calcification with statistical results from real human data will be used in restraint system design and optimization considering population diversity.

VI. ACKNOWLEDGEMENT

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