Individual Representation of Costal Cartilage Calcification in Finite-Element Human Body Models

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I. INTRODUCTION

Calcification or ossification of the costal cartilage taking place throughout adult life produces inhomogeneity of cartilage mid-substance. The local stiffened material in costal cartilage with calcification can affect the mechanical response of the cartilage as well as the ribcage, and this effect is highly dependent on the amount, location, shape and microstructure of calcification [1-2]. By analysing medical images, such as X-Ray, CT and micro-CT, it has been found that the volume of calcification in the costal cartilage increases with age, and that typical patterns of calcification and accumulation rates differ between males and females [3-4]. In current commercial finite element (FE) human body models (HBMs), the costal cartilage is represented as a network of finite elements with homogeneous material properties [5], while the discretised nature of FE meshes allows for modelling of discrete regions with different materials. We have previously [6] laid out a framework to measure costal cartilage calcification in real subjects, to statistically aggregate calcification from multiple individuals to form statistically average amount and patterns of calcification, and to incorporate those average behaviours into current HBMs. It would be desirable for modern HBMs to not only represent average behaviour of a target demographic but also to represent the specific behaviour of a single individual (e.g. specific PMHS subjects during experimental testing). In this paper, we extend our previous framework (which concentrated on population-based average behaviours) to represent the costal cartilage calcification patterns and amounts found in specific individual human subjects.

II. METHODS

Workflow of Modelling Costal Cartilage Calcification

A custom MATLAB program was created to collect and transfer costal cartilage calcification data from clinical CT scans into FE HBMs [6] (Fig. 1). A core concept within the program is an anatomical indexing system that can unambiguously define the physical positions within a costal cartilage network. It identifies any point within a cartilage network by its side (*Side*) and connected rib number (*RibNo*), then the point's position within this segment is specified along the segment's length (*DistFromRib*), along the space ranging from the segment's core to its cortex (*DistFromCore*), and by rotational position in a cross-section through the segment (*AngleWithAnt*). Nodes in FE HBMs and voxels in clinical images can each be anatomically indexed in this consistent system.

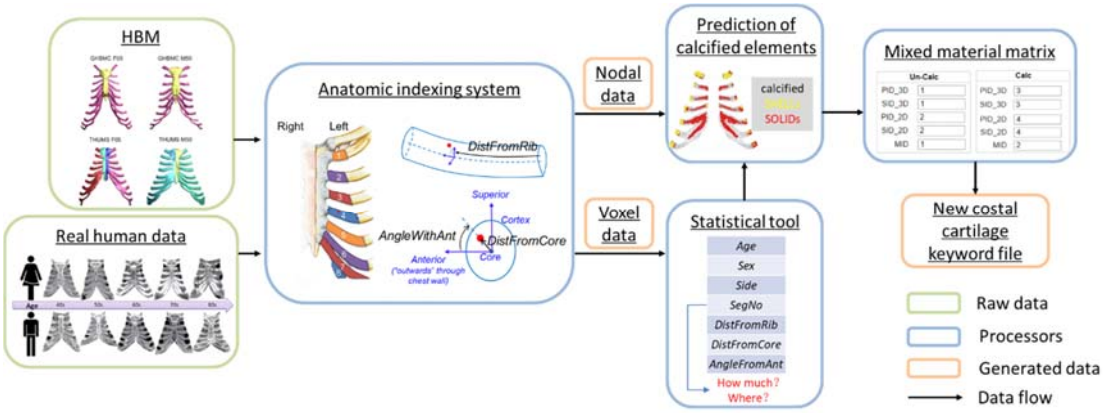

Fig. 1. Workflow of modelling calcified costal cartilage in FE HBMs with real human data.

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Previously [6], we had applied the indexing system to CT scans of 28 individuals (13 females, 15 males) aged from 6 to 90 years and four current FE HBMs (the GHBMC M50 and F05 (Version 4.5) and THUMS M50 and F05 (Version 4.0)). With the metadata of real subjects, we built a statistical tool to use demographic variables (age and sex) to predict: (1) the volume ratio of calcification expected for a given cartilage segment; and (2) the distribution of calcification as a function of the coordinates in the anatomic indexing system described above. Using these statistical tools, we predicted (1) and (2) for a chosen target demographic, and transformed the results into a series of decisions about whether to set individual 2D shell and 3D solid elements in a given HBM mesh to "on" (i.e. calcified) or to "off" (i.e. un-calcified). This produced an updated FE mesh of the costal cartilage that most accurately reflected the average state of calcification for subjects of a given age and sex.

Integrated Module of Statistical Tool for Individual and Population-based Representation

Individual representation of a specific subject and population-based representation can be realised in the same workflow developed above by sharing the same module of statistical tool (Fig. 2). For population-based representation, the statistical model ("SegVolModel") generates an average estimate for cartilage calcification volume ratio, whereas for specific subjects that ratio can be input directly by using an over-fitted statistical model, e.g. a regression tree to realise a mapping to oneself at each data point.

For calcification probability of each position (predicted by "PositProbModel") for a specific individual, such an over-fitted regression tree would be problematic since the node locations in any FE model mesh do not correspond directly to voxel locations in the underlying CT scan. Therefore, we used a bootstrap-aggregated decision tree classifier (similar to that used in the population-based prediction), but this time we trained this model using only the single subject's CT data. The results here adequately captured the general distribution of cartilage calcification, without misrepresenting calcification due to very local (i.e. smaller than mesh element sizes) changes in calcification that could be detected on the underlying CT scan volume.

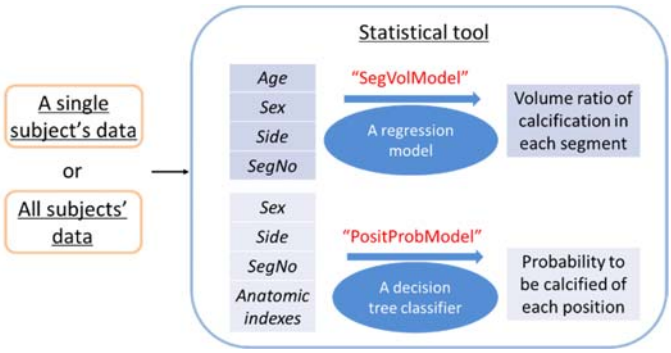


Fig. 2. Integrated module of statistical tool to realise individual and population-based representations.

III. INITIAL FINDINGS

In the workflow integrating individual and population-based representations, by specifying any subject in the data pool or specifying demographic variables (age and sex), the costal cartilage calcification in the upper seven cartilage segments of the specified subject or the average behaviour of the target demographic can be represented in any of the four HBMs (GHBMC M50 and F05, THUMS M50 and F05). Some individual representations of the male in THUMS M50 and the female in THUMS F05 were given for comparisons with the real subjects they represent (Fig. 3). Note that the CT image shown for each subject is only a slice through the cartilage, while the THUMS model is a picture of a 3D object. The regions of calcification observed on a slice of CT image were not all the regions in the real subject that the HBM intended to represent. Individual representations reproduced most locations of calcification observed in CT images, but some locations of calcification in real subjects were lost in HBMs, such as the inferior regions in the 3rd and 4th cartilage segments of the 29YO female and the small regions on the margins of the 42YO male. The typical calcification patterns of the male and the female in the data pool were successfully reflected in their individual representations in FE HBMs. The male exhibited a peripheral pattern with more calcification on the inferior and superior costal cartilage margin (e.g. the 59YO male), whereas the female showed a central pattern with more calcification in the core of costal cartilage cross-sections (e.g. the 90YO female). The different typical patterns can further be quantitively analysed by the relative magnitude between the volume ratio of calcified shell elements on the cortex and the volume

ratio of calcified solid elements in the core in next steps.

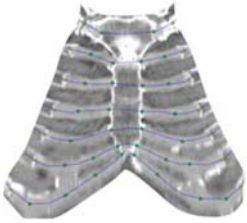
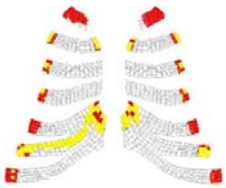
Female			Male		
Age	Subject	THUMS F05	Age	Subject	THUMS M50
29YO			22YO		
37YO			36YO		
41YO			42YO		
49YO			59YO		
74YO			76YO		
90YO			88YO		

Fig. 3. CT images of the upper seven cartilage segments of real subjects and corresponding individual representations in THUMS M50 or THUMS F05 (elements in yellow: shell elements on the cortex labelled as being calcified; elements in red: solid elements in the core labelled as being calcified).

IV. Discussion

Limitations of the Workflow in Individual Representation

While overall correspondence between underlying subject CT image and FE mesh calcification patterns are strong,

there are some minor or local differences, as seen in Fig. 3, which we believe may be due to imperfect image processing or to large element sizes in HBMs. Some bony tissue in the rib/sternum near the sternochondral/interchondral joints was segmented as costal cartilage in image processing and labelled as being calcified in data preparation for the statistical tool. Elements in FE HBMs (with edge lengths of 5–10 mm) are larger than some small regions of calcification observed in real subjects. When the volume of "real" calcification in a cartilage segment was very small and some rib/sternum tissue adjacent to the ends of segments was "mistaken" for calcified cartilage in a real subject, the elements on the ends of the segment in the HBM were labelled as being calcified to contribute to the target volume, while the small volume of "real" calcified cartilage failed to turn on a calcified element as it was much smaller than the size of an element.

As shown in Fig. 3, specific individual patterns in calcification are well-represented by their corresponding subject-specific FE mesh. The most striking differences that remain after subject-specific cartilage delineations seems to relate more to the overall morphology of the cartilage network. Take, for instance, the 74YO female and 90YO female - both females, but they have a striking difference in the overall width vs. height of their chest wall and costal cartilage network. This is not captured merely by adjusting calcification status of elements within a single FE model. It is likely, then, that a combination of mesh morphing to match individual subject morphology along with our subject-specific calcification pattern adjustment would produce FE models that most faithfully represent that subject's chest wall.

Applications of the Integrated Workflow

Forman and Kent [2] built personalised FE models of the costal cartilage with CT images of cadaveric specimens and modelled the calcification with the regions transferred from a specific specimen to the model with the same costal cartilage morphology. With the workflow developed in this study, coordinate schemes of cartilages in real subjects, personalised models or given models can be laid out with the unified anatomic indexing system, and the data from a single subject can be automatically transferred to a personalised model, or any given model, by toggling the module of statistical tool to prediction for individual representation. Representation of various calcification amount and pattern in a model with the same morphology and meshes enables decoupling the influence of calcification on mechanical behaviour from that of costal cartilage morphologies. Individual representation of costal cartilage calcification in a personalised model, along with impact tests performed on corresponding cadaveric specimen, can be applied to material calibration with inverse engineering method, i.e. tuning the parameters of material properties in models to fit the simulation results with the experimental results.

In the field of occupant protection in vehicle crashes, a simulation study has shown that stiffened cartilage material resulted in higher injury risk of rib fractures under the load of diagonal seatbelt [7]. The existence of calcification can also increase the overall stiffness of the costal cartilage and influence the protection effect of restraint systems considering population diversity. Current commercial FE HBMs (GHBMC, THUMS, SAFER, HUMOS, etc.) widely used in the development and assessment of restraint systems need to be improved in the aspect of costal cartilage calcification. With massive population data, in alignment with the development of HBMs with representative statures to cover the population, a limited number of calcification behaviours from a statistical aggregation that represents average typical calcification can be modelled in current FE HBMs, with the module for population-based representation being activated in the workflow.

V. Acknowledgement

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VI. References

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