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Technical Plan For Carotid Artery Modeling Methodology For Far Side Impacts (Preliminary)

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Technical Plan for Carotid Artery Modeling Methodology for Far Side Impacts (Preliminary, draft plan)

For presentation to the Far Side Impact Research Committee

1 Introduction

The purpose of this report is to serve as a draft technical plan for the Virginia Tech – Wake Forest Center for Injury Biomechanics' work in carotid artery injury modeling.

2 Work performed to date

Our efforts have been focused on obtaining the geometrical data necessary for modeling the carotid artery in the region of interest, at the location where a four-point seatbelt would be expected to interact with the neck. With this geometry a three dimensional finite element model of the artery's geometry within the neck is being created that will serve as the structure for all modeling efforts.

2.1 Geometry data

The geometry data for our work came from scans of a patient at Wake Forest University Baptist Medical Center. All protocols pertaining to confidentiality of patient information, confidentiality, and de-identification of patient data, etc were strictly followed. The protocol for use of geometry from clinical medical images was reviewed by Wake Forest's Internal Review Board and approved prior to commencement of work.

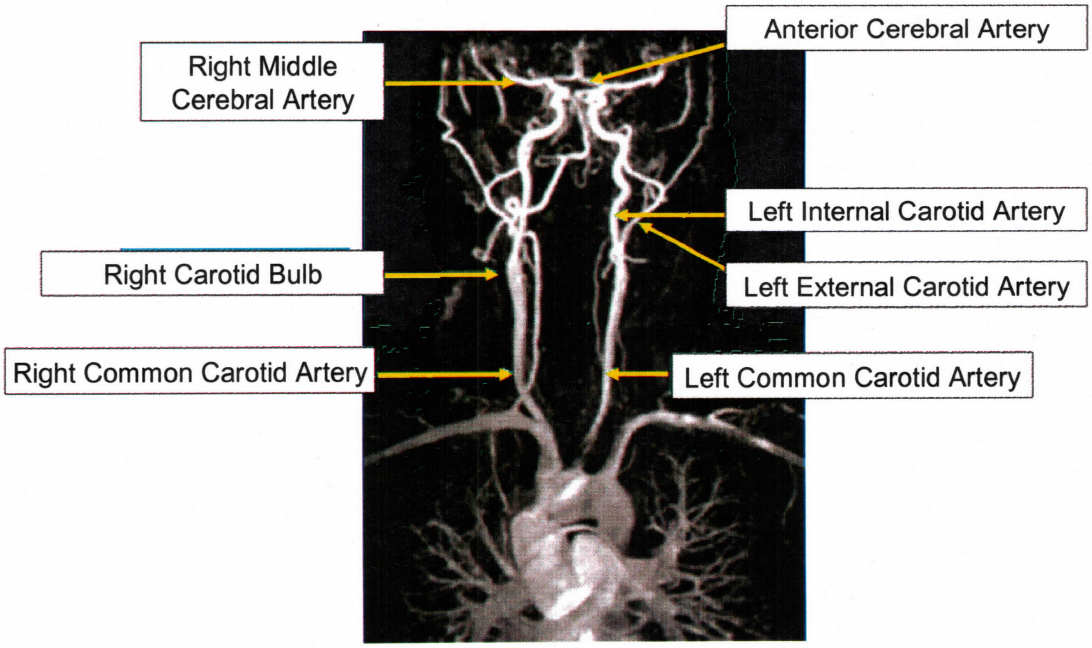


Figure 1. Carotid Artery Anatomy
(adapted from http://www.cme.wisc.edu/online/radiology/carotid/anatomy.htm).

Images were obtained from Computed Tomography (CT) scans of a patient's left carotid from the level of the base of the jaw to the insertion of the carotid artery into the aorta. In Figure 1, the lower bound is readily visible as the insertion of the two carotid arteries into the u shaped aorta at the bottom of the picture. The upper bound would be just above the arrow showing the left internal carotid artery.

Scans were obtained using a General Electric (GE) LightSpeed Pro 16, a clinical CT scanner in common use throughout the United States.

2.2 Patient characteristics

Scans were obtained from a 57 year old male on 9/12/2003. This patient had a history of CAD/CVA or coronary artery disease with cerebrovascular accident (usually stroke). This was a perfusion study using contrast agent ISOVUE 370 to check perfusion throughout the carotid and cerebral arteries. As the carotids were assessed to be normal by a qualified radiologist, this image was assumed to be representative of an average male. A total of 270 slices were obtained, with a slice thickness of 0.625 mm and a resolution of 160 mm x 160 mm with 512x512 image size for a resolution of 3.2 pixels/mm or 0.3125 mm per pixel. The images had a grayscale depth of resolution of 16 bits per pixel.

2.3 Image Segmentation

The carotid artery was segmented using a GE Advantage Workstation, to simplify reconstruction of the carotid. The carotid artery was segmented using a marching cubes algorithm such that the internal surface of the carotid formed a three dimensional surface of finite element trias, or three sided elements.

2.4 Model Development

The element geometry was imported into Engineering Technology Associates FEMB (Finite Element Model Builder) version 28.0 to form the input deck for LS-Dyna version 9.70. For preliminary analysis, a blunt impactor of tip radius

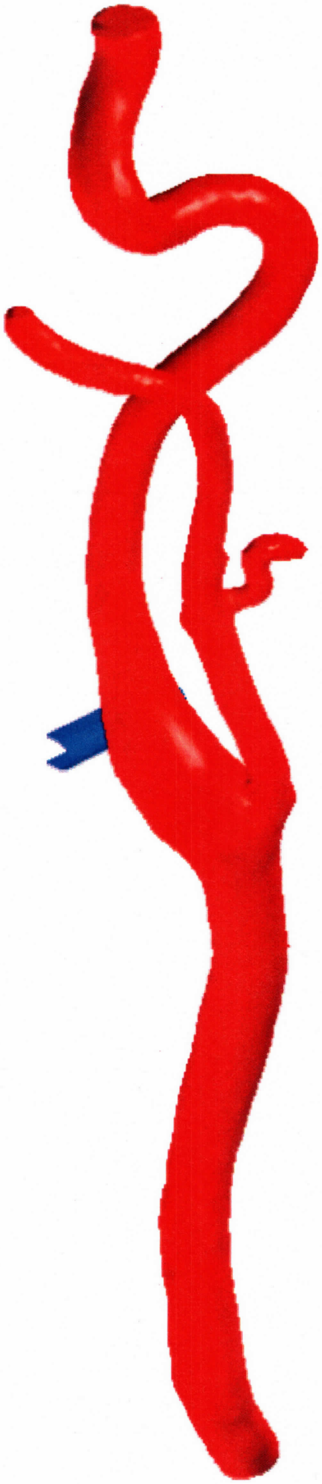


Figure 2. Carotid Artery Geometry from CT Data.

1.5 mm was constructed and impacted into the carotid. The purpose of this exercise was to check contact algorithms and create a preliminary impactor surface, motion constraints, and a profile that can be altered with relevant crash data characteristics. The resulting geometry is shown in Figure 2.

2.5 Initial FEA Results

The initial finite element runs included an initial velocity of 1 m/s for the impactor head, which was placed within a few millimeters of the exterior surface of the carotid. Material properties were approximated to be similar to soft tissues and there was no material filling the carotid to represent blood for these preliminary runs. The resulting Von Mises stress distributions demonstrate stable behavior of the model; however, the model still needs more material data for final validation. Global and local views of stress distribution on the model surface are shown in Figure 3.

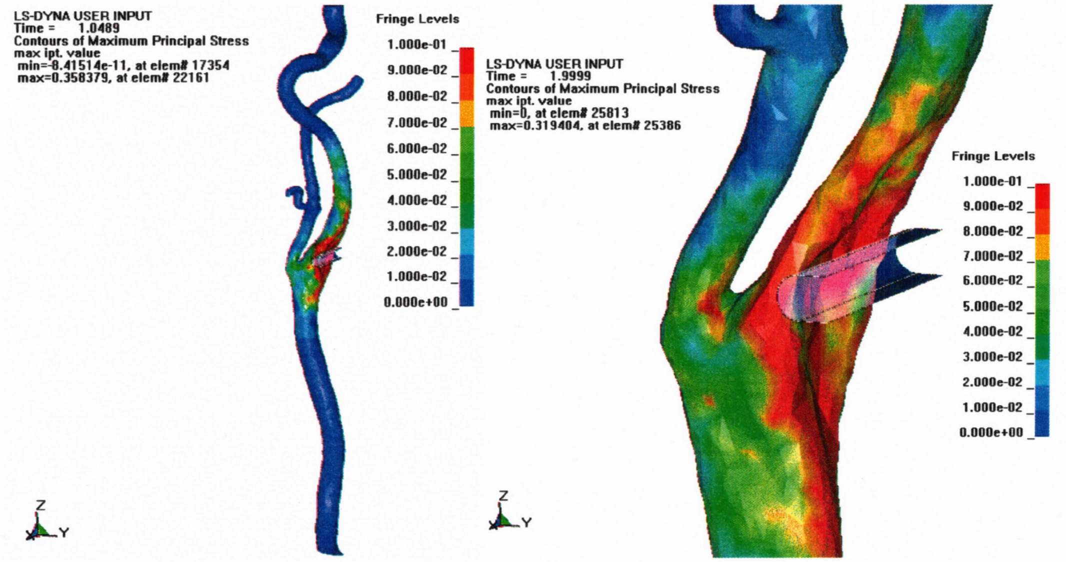
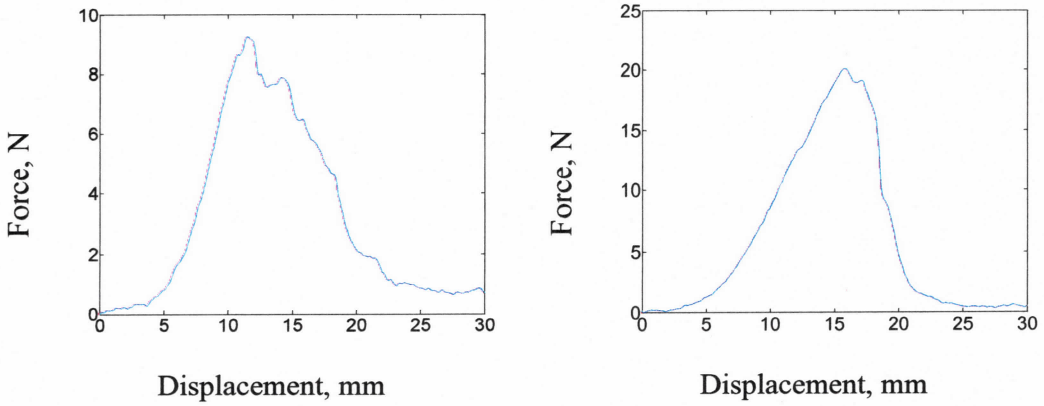


Figure 3. Global and localized view of impactor striking carotid just above level of bifurcation.

2.6 Model Validation (local)

At the current time we have run local validations only. The model was validated using force-displacement curves provided by Medical College of Wisconsin. Test specimens were cut longitudinally, along the axis of the artery. Specimens were preconditioned for five cycles, re-positioned back to the in vitro length, and then the failure test was run. Data was collected at an acquisition rate of 1000 Hz for 50 seconds, for a total of 50,000 datapoints.

For matching model performance to experimental results, the experimental data was filtered using a 1 Hz CFC filter. The reason for this low sampling rate was the large number of samples taken and an essentially static test. The 50,000 sample dataset was then padded symmetrically by replicating the first and last 3000 elements of the dataset array. This was done to eliminate resampling filter startup and finishing irregularities. The data was then resampled at 1/100 of its original sampling rate to obtain 500 datapoints. Padded data was then removed. The force and displacement traces were zeroed (recall that specimens were positioned to in vitro length, assumed to be zero force) to result in the final data for local model validation, shown below.



Force vs. displacement, LICA –
Left internal carotid artery

Specimen dimensions:
length: 18 mm
thickness: 0.89 mm
width: 9.5 mm

Force vs. displacement LCCA –
Left common carotid artery

Specimen dimensions:
length: 22 mm
thickness: 1.77 mm
width: 9.5 mm

Figure 4. LICA and LCCA force-displacement curves obtained from Medical College of Wisconsin.

For these curves, which have a strain-stiffening toe region, a 2-parameter Mooney-Rivlin model is probably appropriate. This model at the current time is preferred to a more specialized soft tissue model which includes transversely orthotropic or fully orthotropic assumptions. At the current time, the test specimens are being modeled using Belytchko-Tsay shell elements with a resolution of element size that gives approximately cubic elements based on the element thickness assumption.

The LCCA arterial segment model dimensions at initial configuration and stress at maximum extension are shown in Figure 5. Force-displacement curve fitting and matching of model response by altering material data and material type are ongoing. The goal is to obtain the best possible match for both local and global response of the model. This model uses a Mooney-Rivlin representation and its material properties are inferred directly from the LCCA force curves from Figure 4.

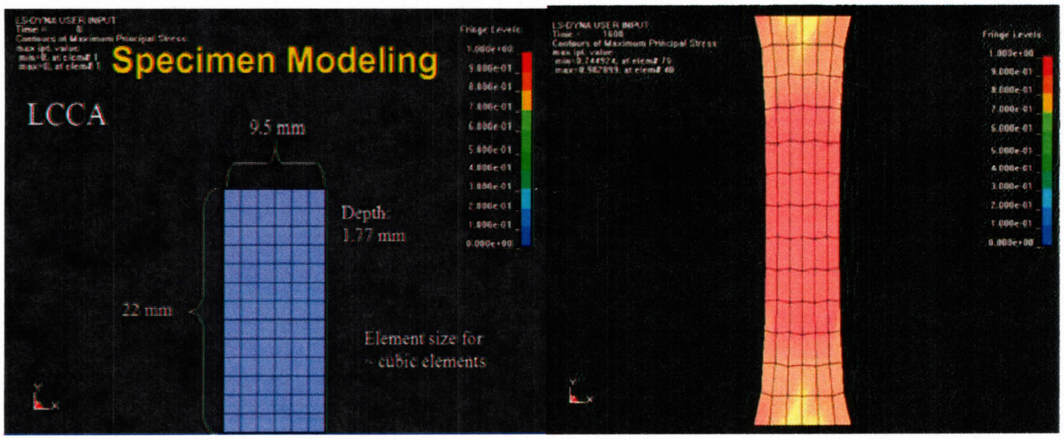


Figure 5. Specimen model for LCCA and peak displacement corresponding to failure. Force-displacement response of this model will be matched with experimental tests to incorporate local material properties into the global model of the carotid.

3 Technical Plan for Future Work

Our technical plan for future work is intended as a draft only for review by the research committee. We see several points which we feel need to be addressed:

3.1 Incorporation of bony anatomy into the model

Geometry representing the bony structure of the neck from above the top portion of the carotid model to below the bottom portion will be incorporated. The purpose of this geometry should be that its displacement and motion can be controlled such that it will interact with the arterial structure (through soft tissues) if needed. This structure will not be intended to accurately interpret forces, or to model neck motion in response to an applied acceleration field. Instead, established neck models that have been widely validated will be used to obtain resulting vertebral body motions. Our approach will be to take the kinematics from the kinematically validated neck models and apply them to our model to predict injury.

3.2 Incorporation of soft tissues surrounding carotid

Soft tissues surrounding the carotid such as muscle, fat, other arterial structures, and skin will be incorporated. However, most of these structures will not be independently modeled. While some effort may be made to incorporate different properties for the skin, the current plan is to fill in the void space surrounding the carotid up to the surface of bony structures, with a homogenous, isotropic medium. This volume will be filled with tetrahedral elements so that the interaction of the carotid with the hard structures of the neck and any impacting structures (seat belt, vehicle intrusions, etc) will be more realistic. However, it is beyond the scope of the proposed work to model all of the individual muscles, muscle tensions, etc to predict the arterial damage.

3.3 Incorporation of additional material data

Additional material data should probably include data from circumferential testing of carotid segments, as well as additional tests so that some data averaging may be performed. It is well known that the properties of arteries are different in the circumferential vs. longitudinal directions. Modeling this difference may be important. Because it adds a level of complexity to the meshing and material assignment, it may not be feasible. Thus, we would at least like to test what the difference in mechanical behavior between the circumferential and longitudinal directions is, and decide whether some material property averaging is warranted. If it is not, it must be determined which direction of loading dominates the failure response by comparing experimental tests.

3.4 *Incorporation of layering of materials*

As we discussed at the last meeting of the Far Side research group, the carotid has a three-layered structure consisting of the intima, media, and adventitia. The intima consists of basal lamina and endothelial cells, and is very thin and contributes little mechanical strength to the arterial wall. The media is comprised primarily of smooth muscle cells and is responsible for the material behavior of the arteries in the physiological range of strain, and particularly in a living environment where vascular tone is present. The adventitia contains a layer of collagen with a wavy orientation that will straighten out and contribute strongly to mechanics as the artery reaches peak distension. So, before macroscopic failure of the tissue, you must go through this full range of mechanics. However, intimal damage is a serious biochemical concern because it tends to initiate clotting and can cause stroke and can, over long term, result in intimal hyperplasia. Medial damage is a contributing factor to dissection, where blood can get behind the media, but still be contained by the adventitia, resulting in the closing off of the artery. Adventitial damage, of course, in arteries where there is high blood pressure, can result in internal damage and may represent the most imminent danger. So, each mechanism has a different mechanical cause and may be worthy of an independent layer in the model for prediction. The only alternative to trying to predict failure layer by layer is trying to predict each injury indirectly by a strain assumption in a single-layered representation. Either way, this will require mechanical testing to look at failure of each layer independently, and careful documentation of the failure. The most important decision to be made at the present time is which injuries are most important with regard to far side impacts and what is the desired level of complexity of the model. Switching to a layered model will require altering the material model used to a layered, composite representation of the tissue.

4 Conclusions

The geometry of the carotid has been created from medical images (CT) and preliminary validation has begun. Specifically we have also modeled a local material specimen for the LCCA and begun fitting to the University of Wisconsin data. There is validation remaining to be completed and this should include global testing as well. The material representation should be investigated for whether it will be sufficient to predict failure modes of interest. Geometry of skin and bony structure in the neck needs to be added to the model and the tissue surrounding the carotid between the skin and the bone will be added to the model. A method for matching the kinematics of our model to outputs from more accurate overall neck models will be devised, and the resulting model will be used to predict carotid artery injury.