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A Comparison of Methods for Modeling Neck Muscle Wrapping in Finite Element Models

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ABSTRACT

Human neck musculature plays an important structural role during tension and bending modes of neck loading. Computational models of the head and neck require that the muscles follow the curvature of the neck during bending to maintain anatomically correct lines of action. The method used to model muscle wrapping affects head kinematics, neck loads, model stability and computational runtimes. This study presents a review of existing methods to model muscle wrapping. One additional method that takes advantage of a new contact interaction available within LS-DYNA (LSTC, Livermore, CA) is also presented. A comparison is made between methods and their effects on head kinematics, neck loads, model stability and computational runtimes during simulated frontal impact and airbag loading. This comparison shows that the new contact interaction within LS-DYNA has advantages over the other methods.

INTRODUCTION

The human neck consists of two primary structural components, the muscular spine and the ligamentous spine. It has been shown that the muscular spine contributes significantly to the strength and stiffness of the neck during tension and bending modes of neck loading (Chancey et al., 2003; Van Ee et al., 2000). Since these modes of loading are manifest during motor vehicle crashes, understanding the contribution of the muscular spine is important to understanding neck injury.

Computational finite element models of the head and neck are useful tools to investigate the contribution of the muscular spine (Figure 1). One challenge of modeling the neck is modeling the interaction between the musculature and ligamentous spine. Several head and neck models have modeled neck muscles as single-segment 1D elements (Camacho et al., 1997; de Jager et al., 1994; de Jager et al., 1996; Li et al., 1991; Merrill et al., 1984; Oi et al., 2004; Van Ee et al., 2000). These single segment muscles are only able to interact with the spine at their connected endpoints. If a muscle spans several cervical vertebrae, the muscle lacks the ability to interact with those spanned vertebra. If the model is loaded in such

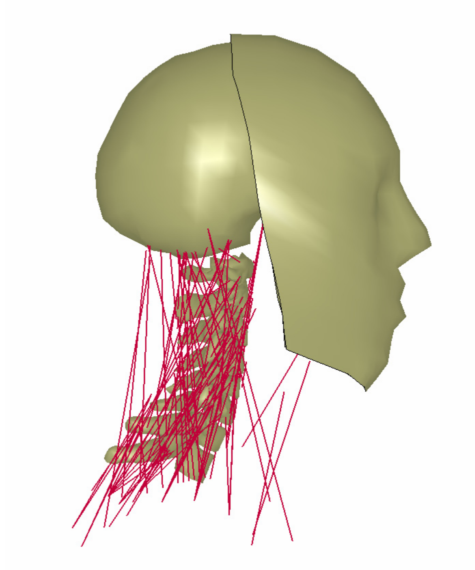


Figure 1: Computational model of the human head and neck.

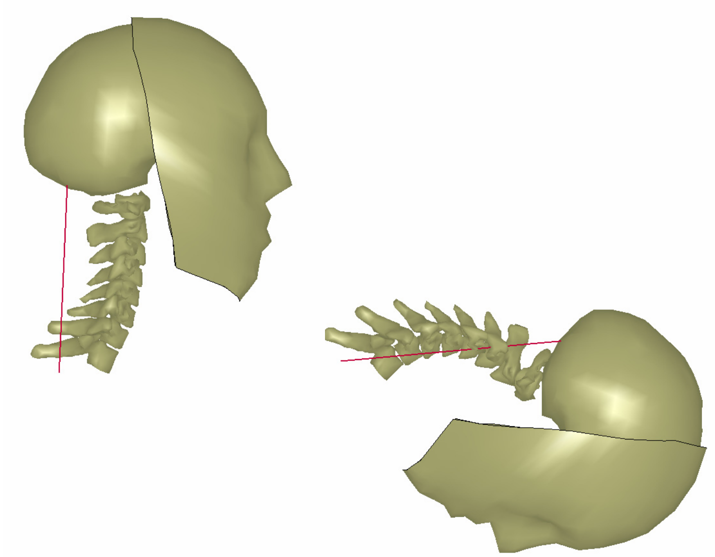


Figure 2: When neck musculature is modeled as single-segment 1D elements and no interaction between the muscular and ligamentous spine is modeled, the muscles will pass through the ligamentous spine resulting in non-physiological muscle loading line-of-action. Shown is the semispinalis capitis.

a manner that results in large neck bending (extension or flexion), the muscle will pass through the underlying ligamentous spine. The muscle passing through the vertebrae results in non-anatomical muscle loading line of action (Figure 2). To solve this problem, methods to model muscle wrapping have been used. The viable methods can be classified in one of two categories: multi-segmented muscles and sliding contact interaction. Other methods of muscle wrapping have been used but lack the ability to model active contractile muscle properties (Golinski and Gentle, 2005; Hedenstierna et al., 2007; Meyer et al., 2004; Tropiano et al., 2004).

The first method for modeling muscle wrapping is multi-segment muscles (Brolin et al., 2005; Deng and Goldsmith, 1987; Luo and Goldsmith, 1991; Panzer, 2006; Pontius and Liu, 1976; Wittek and Kajzer, 1998; Wittek et al., 2001). This method divides the muscle into discrete segments. The intersegmental nodes are then rigidly attached to adjacent vertebra. The rigid attachment maintains a fixed distance between the ligamentous spine and the muscular spine.

The second method for modeling muscle wrapping is through a sliding contact interaction. The contact interaction is dependent on the computational software. Several researchers have used MADYMO (TNO, Delft, Netherlands) (Brelin-Fornari et al., 2005; Stemper et al., 2004; van der Horst, 2002; van der Horst et al., 1997) or SIMM (MusculoGraphics, Inc, Santa Rosa, CA) (Kruidhof and Pandy, 2006; Vasavada et al., 1998). Recently, LS-DYNA (LSTC, Livermore, CA) released a new contact interaction called *CONTACT_GUIDED_CABLE that can be used as a sliding contact to model muscular wrapping. This contact interaction guides 1D muscle elements through a series of nodes that are rigidly attached to adjacent vertebra. A sliding friction and contact stiffness can be defined.

The current study was a comparison of methods for modeling neck muscle wrapping in finite element models of the head a neck. The effects of muscle wrapping method on head kinematics, neck load, model stability and computational runtime during simulated frontal impact and out-of-position (OOP) airbag impact are presented.

METHODS

A validated computational model of the head and neck (Camacho et al., 1997; Chancey et al., 2003) was used to compare the methods for modeling muscle wrapping. The model is a hybrid lumped parameter and finite element osteoligamentous cervical spine (Figure 1). It consists of eight rigid body vertebrae, the seven cervical and the first thoracic (T1), and a rigid body head connected by eight joints. Each joint consists of three discrete element pairs comprised of a nonlinear spring and linear damper in parallel. The three pairs were: compression-tension, anteroposterior shear, and flexion-extension rotation. Twenty-three pairs of muscle were represented in the model. Each muscle force is the product of the muscle physical cross sectional area (PCSA) and muscle stress. Each muscle stress is the sum of the nonlinear passive muscle response and nonlinear active muscle response. The nonlinear active muscle response is scaled by a muscle activation value of 0 to 1 representing no muscle activation and full muscle activation, respectively. The muscle activations used in this study were obtained by minimizing the force required to hold the head upright against the force of gravity (Chancey et al., 2003). This represents a relaxed individual with no pre-impact awareness. LS-DYNA was used as the computational solver. Three models were used for the comparison. The only parameters changed between the models were the method for modeling muscle wrapping.

The first computational model utilized single-segment muscles. These 1D elements were not able to model muscle wrapping. The endpoints of the elements were attached at the insertion and origin of the modeled muscle. The only interactions between the muscle and the ligamentous spine were at the endpoints.

The second computational model utilized multi-segment muscles in which each muscle was divided into segments. The number of 1D element segments used for a single muscle was dependent on the number of vertebra the muscle spanned. For every vertebra spanned, the muscle was segmented and the intersegmental node was rigidly attached to the spanned vertebrae. The intersegmental nodes of a single muscle lay on the insertion to origin vector of the muscle and located vertically at the same height as the spanned vertebral center of gravity (CG).

The third computational model utilized a sliding contact interaction between the muscles and the vertebrae. The contact interaction used was the LS-DYNA *CONTACT_GUIDED_CABLE. Each muscle was divided into twelve evenly divided segments. A series of contact nodes were rigidly attached to spanned vertebra. The number of nodes was dependent on the number of vertebrae spanned. The nodes were located along the insertion to origin vector of the muscle at the same height as the spanned vertebral CGs. The contact guided cable interaction specified that the segmented muscle be guided through the series of contact nodes. The default contact interaction was specified, as was a frictionless contact interaction.

The three computational models, each with the different method for modeling muscle wrapping, were used in two simulations: simulated frontal impact and simulated out-of-position airbag impact. The simulated frontal impacts were based on estimates made by Thunnissen et al. (1995) of NBDL volunteer 15 g frontal impacts (Ewing et al., 1968). T1 linear x-acceleration and y-rotational displacement were prescribed. Head and neck kinematics corridors estimated by Thunnison et al. were included for reference purposes. Simulated out-of-position airbag impacts were based on simulations performed by Nightingale et al. (2000). An equivalent z-directional force rate of 10 kN/s to 6 kN was applied at the head CG. Both the frontal and OOP airbag impact simulations included gravitational forces.

The effect of method for modeling muscle wrapping on computational efficiency was studied. The time to complete each run was recorded. Simulations were run on a Dell Precision Dual Core Intel 2.4 GHz desktop running LS-DYNA version 971d R3 beta, revision 11784.

RESULTS

Frontal Impact

Modeling muscle wrapping had a large effect on head and neck kinematics during simulated frontal impact. Comparing head CG displacement (Figure 3), the peak head CG displacement of the single-segment model was 0.294 m. This was 0.052 m (18%) more resultant displacement than the 0.242 m peak head CG displacement of the multi-segment model and 0.036 m (12%) more than the 0.258 m peak head CG displacement of the contact guided cable model. Comparing head rotation (Figure 4), the peak head rotation of the single-segment model was 132°. This was 39° (30%) more rotation than the 93° peak head rotation of the multi-segment model and 37° (28%) more rotation than the 95° peak head rotation of the contact guided cable model. Finally, comparing neck rotation (Figure 5), the peak neck rotation of the single-segment

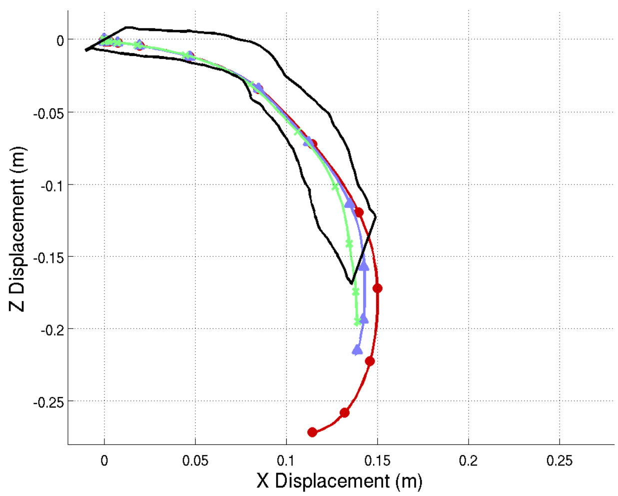


Figure 3: Head CG displacement results during simulated frontal impact.

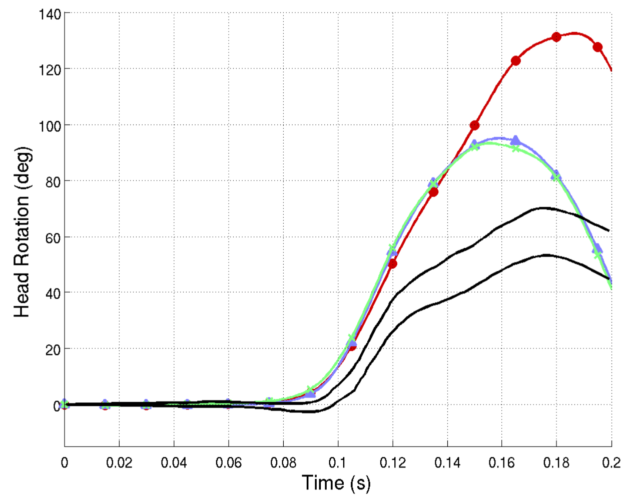


Figure 4: Head rotational displacement results during simulated frontal impact.

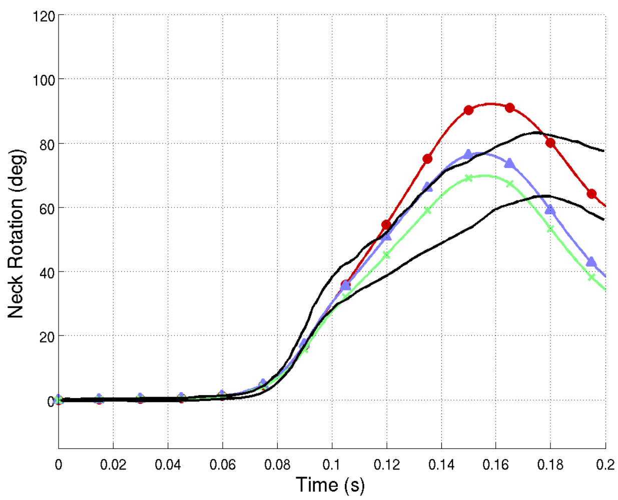
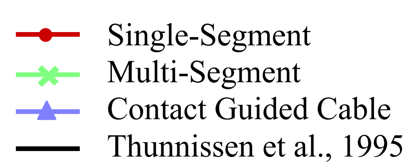


Figure 5: Neck rotational displacement results during simulated frontal impact.



model was 92°. This was 22° (24%) more rotation than the 70° peak neck rotation of the multi-segment model and 15° (16%) more rotation than the 77° peak neck rotation of the contact guided cable model. This over extension and rotation resulted in the mandible passing through the ligamentous spine.

The method of modeling muscle wrapping did not have a large effect on head and neck kinematics during simulated frontal impact. The peak head resultant displacement of the multi-segment model was 0.016 m (6%) less than the contact guided cable model. The peak head rotation of the multi-segment model was 2° (2%) less than the contact guided cable model. The peak neck rotation of the multi-segment model was 7° (9%) less than the contact guided cable model.

Modeling muscle wrapping affected computational efficiencies (Table 1). The multi-segment model required 30% more time and the contact guided cable model required 80% more time than the single-segment model.

Table 1. The effect of muscle wrapping method on computational run time during simulated frontal impact. Simulations were run on a Dell Precision Dual Core Intel 2.4 GHz desktop running LS-DYNA version 971d R3 beta, revision 11784.

Wrapping Method	Computational time	Normalized time
Single-Segment	156 s	1
Multi-Segment	203 s	1.3
Contact Guided Cable	276 s	1.8

Out-of-position airbag impact

Modeling muscle wrapping or method for modeling muscle wrapping did not have a large effect on head kinematics during simulated OOP airbag impact. The peak head resultant displacements for the three models were within 4% of each other at 40.4, 38.8, and 40.4 mm for the single-segment, multi-segment, and contact guided cable models, respectively. The peak head extension rotation for the three models were within 8% of each other at 19.3°, 17.9°, and 18.9° for the single-segment, multi-segment, and contact guided cable models respectively.

The method of modeling muscle wrapping had a significant effect on the tensions that developed in the individual muscles during simulated OOP airbag impact. At peak head displacement, the tension in a strand of the semispinalis capitis was compared (Table 2). The single-segment model had a tension of 45N. The contact guided cable model had a tension of 47 N. The multi-segment model had a ten-fold variance in the discrete segment tensions of the semispinalis capitis, which ranged from 7 N to 72 N.

Table 2. The effect of muscle wrapping method on neck muscle tension of an individual muscle strand at peak head displacement during simulated OOP airbag impact.

Wrapping Method	Semispinalis Capitis Tension
Single-Segment	45 N
Multi-Segment	7 N to 72 N
Contact Guided Cable	47 N

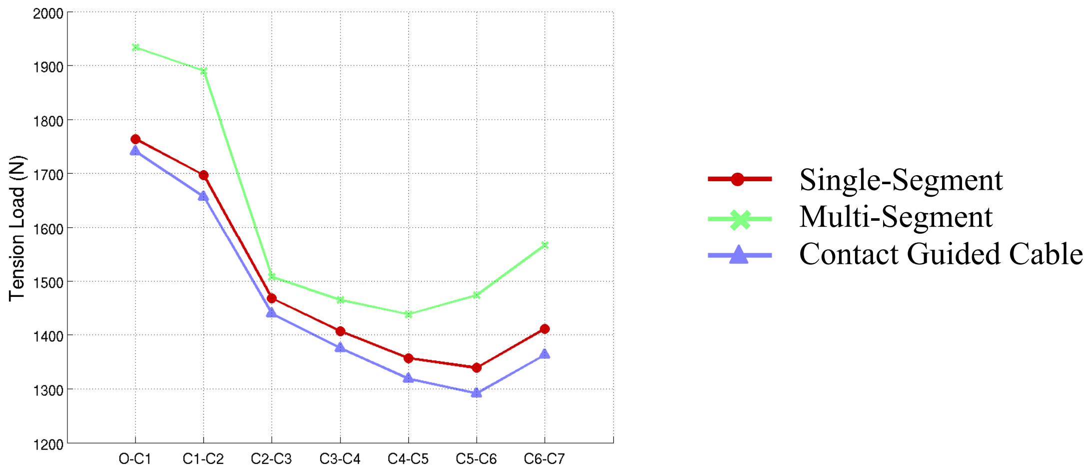


Figure 6: Neck motion segment tension load results at an applied load of 2960 N during simulated out-of-position airbag impact.

The method of modeling muscle wrapping also had an effect on the tension in the neck motion segments. The tension in the neck motion segments were compared an applied force of 2960 N to the head CG (Figure 6). The O-C1 motion segment of the multi-segment model reached 1930 N, the failure limit of the upper cervical spine (Chancey et al., 2003; Van Ee et al., 2000), thus predicting neck injury. The load in the OC1 motion segment of the single-segment and contact guided cable at the same applied load was 1764 N and 1741 N -- respectively, 9% and 10 % below the failure limit. The multi-segment model also experienced higher tensions in the upper cervical spine motion segments as compared to the lower cervical spine motion segments as compared to the single-segment and contact guided cable models.

DISCUSSION

Understanding the contribution of the muscular spine is important to understanding the human neck during loading and injury. A tool used to understand that contribution is computational models of the head and neck. One challenge is the ability to model the interaction between the muscular spine and the ligamentous spine, which results in muscle wrapping. In this study, the effects of the method for modeling muscle wrapping were investigated.

During loading conditions that induce flexion or extension of the neck, such as frontal impact, modeling muscle wrapping had a significant effect on head kinematics. When muscle wrapping was not modeled, using single-segment muscles, the head over-displaced and rotated, resulting in the non-physiological passing of the mandible through the ligamentous spine. This resulted because of non-anatomical muscle loading lines of actions.

Also during loading conditions that induce flexion or extension of the neck, such as frontal impact, the method for modeling muscle wrapping did not seem to significantly effect head kinematic response. Using either multi-segment muscle or contact guided cable muscles, muscle-loading lines of actions remained anatomical and head displacement and rotation were correctly modeled.

During loading conditions that produce tension of the neck, such as out-of-position airbag impacts, the method for modeling muscle wrapping had a significant effect on neck kinetics. Since muscle-wrapping effects are intended during bending, muscle wrapping should not strongly affect results during neck tension with minimal bending. When muscle wrapping was modeled using multi-segment muscles rigidly attached to vertebra, tensions along the length of a muscle varied depending on the muscle segment and vertebral kinematics. That variance then affected motion segment forces. Since injury prediction is based on injury thresholds of the motion segment, using multi-segmented muscles altered injury prediction. Contact guided cable muscles maintained correct motion segment forces and injury prediction.

One limitation of this study was the scope. The purpose of the study was only to examine the effect of the method for modeling muscle wrapping. During simulated frontal impact, none of the models presented fit the NBDL corridors as estimated by Thunnison et al. One major reason was level of muscle activation used in this study. The tests were run at a constant minimal activation. Further studies are being conducted to understand and fit the corridors.

SUMMARY

When designing and utilizing computational models of the head and neck for use in investigating motor vehicle accidents:

- For modes of loading that include neck bending, a method for muscle wrapping needs to be utilized.
- The method for muscle wrapping does not have a strong effect on head kinematics.
- The method for muscle wrapping does affect neck kinetics and injury prediction.

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DISCUSSION

PAPER: **A Comparison of Methods for Modeling Neck Musculature Wrapping in Finite Element Models**

PRESENTER: ***Alan Dibb, Injury and Orthopaedic Biomechanics Laboratory***

QUESTION: *Martin Annett , Johns Hopkins University*
Did you try using contact automatic general? That's one that's if you're trying to interface beams with solid elements. It tends to work in LS-DYNA. I don't know if it's better or worse than their new capabilities. It all tends to be, you know--

ANSWER: One of the reasons we did this was because it used 1D elements and that's how, traditionally, we have modeled the muscles as springs in parallel.

Q: Okay.

A: And, it was just an easy transition to go to sliding contact, the contact guiding cable. And I tried other ones, but I couldn't match the tension within the muscles.

Q: *Joel Stitzel, Wake Forest University*
Really nice presentation. I liked it. It struck me that with muscles, like with every other piece of anatomy in the body, ultimately, we end up insisting that it be geometrically similar to the anatomy in our bodies and that's true with bone and a lot of the soft tissues. But then with muscles, we're quick to decide that these need to be beams and I think that's driven by the capabilities that we have with beams. But I was curious if you felt that the ultimate, sort of, future solution to this would be modeling the 3-dimensionality, the 3-dimensional structure of the muscle, by trying to incorporate the tension, you know, relaxation characteristics of it within that model.

A: Other researchers have tried that. The cost—The computational time cost, I know, is extremely high. I don't know if you noticed the times. We need to kind of keep the times down because we do optimizations of the muscles to try to figure out the activations. But I do agree that an ultimate would be to have 3-dimensional. There's also a challenge with active muscles: how to activate an actual solid element to actually contract. So that's another challenge. We're moving to solid elements.

Q: So you think, from an injury prediction standpoint, you think that that will be a better solution in the future?

A: I think that's a way to go. I think right now, right where we're at: not quite yet.

Q: Okay. Thanks.

Q: *Guy Nusholtz, DaimlerChrysler*
Don't count on getting your code fixed in any time in the near future without having some other sneaky thing that falls into the different elements. How do you know that—Of the different methods that you're looking at, how do you know that's real and not just a numerical trick or a numerical procedure that's put in there? Have you done anything to evaluate it, outside of the gross body motion?

A: You mean--?

Q: You've got—In some cases where you just attach a line and you've got them up against a catch directly.

A: Um hm.

Q: And you've got them sliding through cable.

A: Yeah.

Q: How do you know that that's not numerics and it's something that's really representative of the physics that's occurring?

A: I'm not—

Q: Or do you?

A: I don't at this time.

Q: Okay. That answers that question.

A: There's more work that needs to be done with this in different modes of loading and things like that to fully understand it.

Q: Okay. Thank you.

Q: *Erik Takhounts, NHTSA*
I was wondering if you can use the same methods of external nodes with deformable vertebra?

A: You can. The few examples they sent me from LSTC: They actually model a rebar through concrete and so they model the concrete of solid elements. So you can do that I know of, but we—right now, this node is rigidly attached to the vertebra.

Q: Okay. Another question is: How do you activate the muscles in each one of these muscles? Do you activate each segment or you activate the whole muscle?

A: You use the same activation for the whole muscle and each of the muscles—Each of these things use the same definition of a muscle in LSTC. You can either use non-linear springs or you can use their hill muscles that's included within it, the LSTCs—I mean LS-DYNA.

Q: Okay.