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# A Study of Muscle Activation in a Mathematical Model of the Human Head and Neck

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# A STUDY OF MUSCLE ACTIVATION IN A MATHEMATICAL MODEL OF THE HUMAN HEAD AND NECK

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## 1. ABSTRACT

A model of the human head and neck that incorporates active and passive muscles is utilized in the analysis of non-impact loading in high “g” environments. The active muscles have the capability to be activated partially and in different combinations. The model is implemented in MADYMO using lumped parameters and Hill muscles. A comparison of simulation results with experimental data, generated by the Naval Biodynamics Laboratory (NBDL) for neck flexion and rebound, shows excellent agreement for a 15g impulsive load.

## 2. INTRODUCTION

Study of the kinematics of the human neck in a “high-g” environment is a difficult task due to the number and complexity of the muscles in the cervical region. Data obtained with cadavers is limited since they lack live, active muscles. Mathematical models of the cervical spine are a useful tool if the model parameters are accurate. Previous computational head/neck models which incorporated active muscles based the onset of activation (extensors only) on an estimate (or range) of reaction time(s). The same peak activation was assumed for all extensors, the flexors were not activated, and deactivation was not addressed. This project was undertaken to develop an activation scheme based on muscle characteristics, specifically the muscle change in length, and also apply it to deactivation.

Keywords: muscle modeling, Hill muscle, muscle activation

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## 3. METHODS

A lumped parameter head and neck model based on the work of Deng and Goldsmith [1] and de Jager [2] was created using MADYMO, a commercially available, rigid body/finite element, dynamic analysis package. The three-dimensional model consists of ten rigid bodies: the head, the seven cervical vertebrae (C1-C7) and the two thoracic vertebrae (T1-T2). Force models that represent the intervertebral joints and fifteen pairs of active muscles join them. The complete model is symmetric about the mid-sagittal plane. The direction of the Cartesian coordinate system of the inertial frame was aligned to correspond to the coordinate system used in the validation tests from NBDL. The coordinate systems of the bodies are defined at the joints (except for T2, which is aligned with its center of mass). Figure 1 depicts the model's rigid bodies and global coordinate system. The model uses body-fixed reference frames for the measurement of displacement parameters and Bryant angles to describe three-dimensional rotations of each body relative to its adjacent body. Large motions are assumed, but it is presumed with justification, that no combination of Bryant angles that result in numerical singularity occur. Geometric, mass, and joint properties are described in detail in [3].

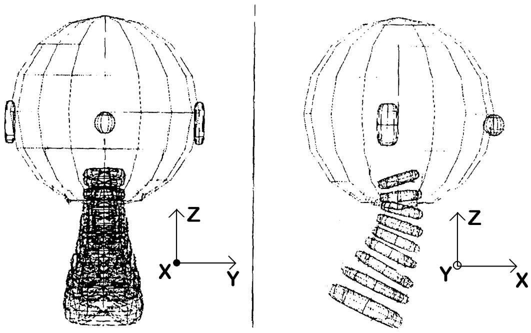



Figure 1: Head/neck model with rigid segments, muscles and associated coordinate system

The active muscles were modeled using Hill's methodology with a contractile active element in parallel with a passive element. Therefore, the total force generated by each muscle is

$$F_T = F_{ce} + F_{pe} \tag{2}$$

where $F_{ce}$ is the force output of the contractile element and $F_{pe}$ is the force output of the passive element.

In the Hill model, the contractile element produces the force generated by the cross bridges of the muscle. This is the internal force created by the chemical reaction within the muscle. The input of the contractile element is a neural impulse. The output is a force ($F_{ce}$) which is a function of the muscle length ($f_l(l_r)$), its rate of change of length or velocity ($f_h(v_r)$), activation level ($A$), and maximum force available at maximum activation ($F_{max}$) [4] or

$$F_{ce} = A\, F_{max}\, f_h(v_r)\, f_l(l_r) \tag{3}$$

A list of muscle computational parameters for the 15 muscle pairs including $F_{max}$, the $f_h(v_r)$ relationship, and the $f_l(l_r)$ relationship are listed in [3].

Activation is a two step process: neural excitation of the muscle and onset of muscle activation. Hill [5] defines the "active state" as the tension that the contractile element would generate, without lengthening or shortening, after the beginning of excitation.

There is little data on the stimulation of activation. A study by Forssberg and Hirschfeld [6] indicates that there is a loose correlation between muscle length and activation and that environmental factors (i.e. vision) could activate a muscle. For this model, muscle length was used as the sole criteria for activation.

Many activation models have been propose, (e.g. logical, linear, or second order), but with a complex system such as the head/neck a complicated activation/deactivation scheme would be counterproductive. Bahler [7] reports that a linear activation scheme with the numeric value of activation ranging from 0 (.005 is reported for muscles at rest) to 1 (full activation) is adequate. The simplicity and accuracy of such a model makes it ideal for activating a large set of muscles. Referring to the work of Winters and Stark [8] the rate of activation was determined to be 10% per 10 ms.

Little information exists regarding deactivation of muscles. Hill [5] concludes that deactivation is slower than activation. Bahler [7] classifies the deactivation time as 5 times longer (50 ms) than activation (10 ms). Winters and Stark [8] report the deactivation rate as 4 times slower. Therefore, in this model deactivation was defined as a linear process with the deactivation at a rate of 10% per 40 ms.

Once a neural impulse is applied to a muscle, there is a lag time between the impulse and the activation of the muscle. This time is called the latent period. Vander [9] reports the time of the latent period as 10 ms.. In this model, a 20 ms delay was set before the onset of the activation or deactivation of a muscle with 10 ms for determination of the action potential (10 ms of increasing or decreasing muscle velocity) and a 10 ms lag. Figure 2 depicts the activation/deactivation scheme applied to the trapezius (an extensor), based on its muscle length, during the validation.

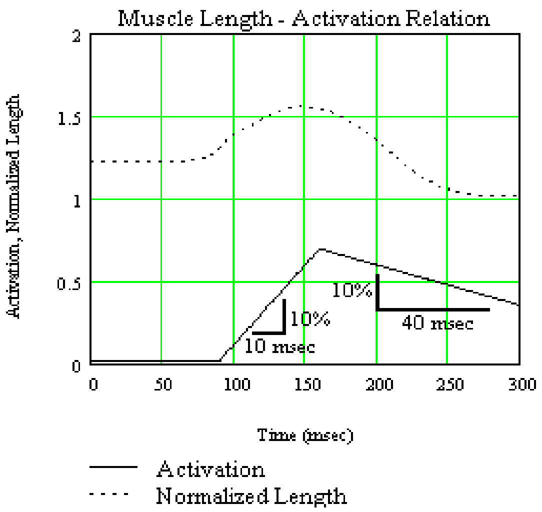



Figure 2: Muscle activation program with respect to normalized muscle length

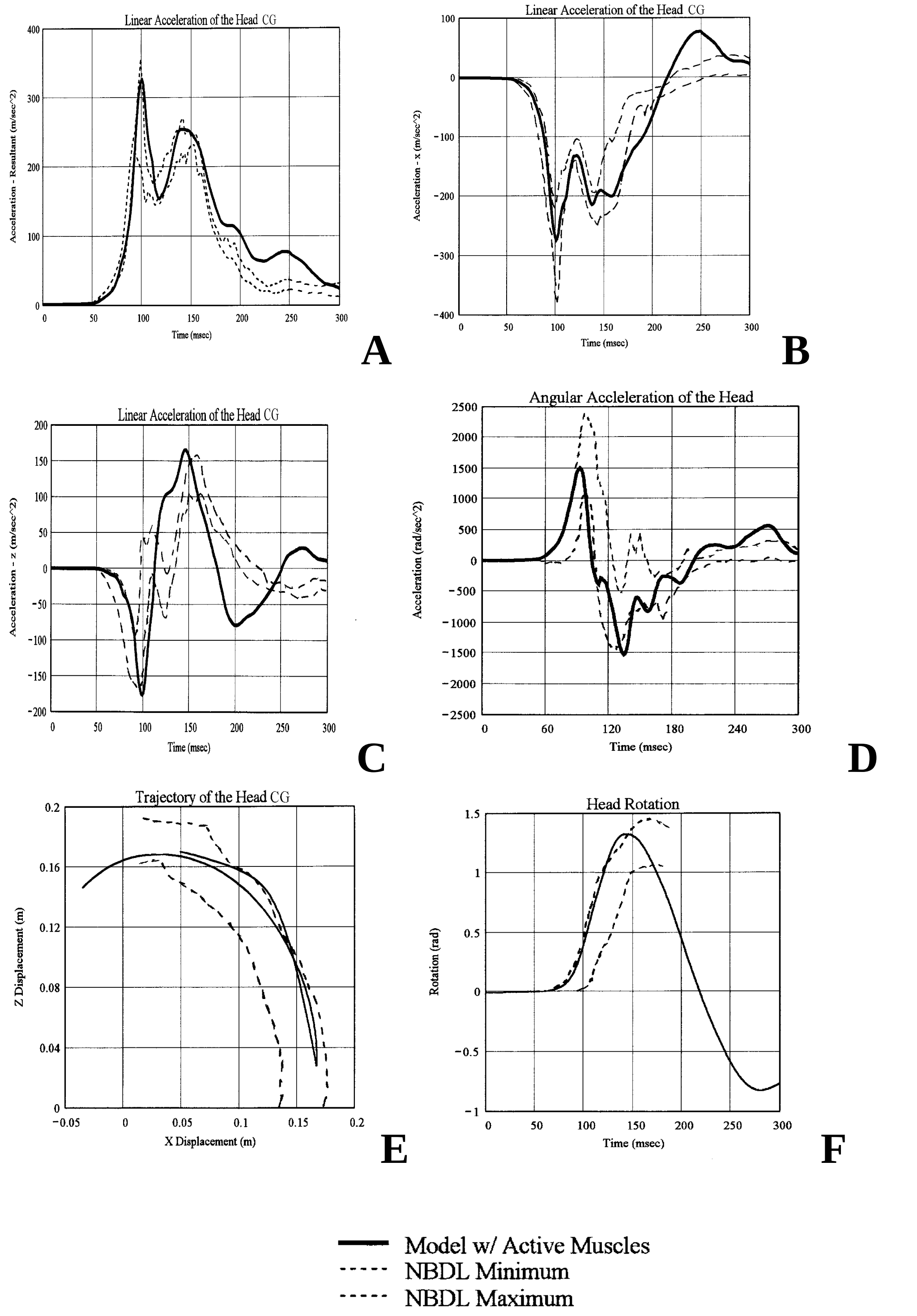
4. RESULTS

Head kinematics resulting from an applied linear acceleration of T1 is presented in Figures 3A through 3G. The solid lines represent the response of the model with a variable activation/deactivation scheme. The dotted lines represent an envelope of head response bounded by the high and low values of nine “high g” (15g) tests generated by NBDL on human volunteers.

Activation of the contractile element of the neck muscles varied in magnitude from 0.5% to 70% depending on the muscle length. At the initial onset of neck flexion, all of the flexors shortened except for the longus capitis and the longus colli. These two muscles lengthened since the neck structure lengthened (head extended out along the z-axis), but the longus colli did not sustain this lengthening for longer than 20 ms and, therefore, did not activate. The longus capitus was activated for a short duration, deactivated, and then activated again when lengthened during head rebound. All of the extensors did lengthen to varying degrees, and did activate after 90 ms of onset of the sled pulse. Deactivation began 70 ms later. The extensors did not reactivate during this analysis. Most flexors began to activate at 180 ms and began to deactivate 70 ms later. Due to the symmetrical nature of flexion, all of the extensors activated at the same time. Even though the rate of elongation varied for each muscle, they began to shorten at the same time therefore, deactivating in unison. The same was true for the flexors (except for the longis capitis). Table 1 lists the activation/deactivation properties of the neck muscles.

Table 1: Muscle activation/deactivation in x-direction loading of the head/neck model

| Muscle | Activated (msec) | Deactivated (msec) | Peak Activation (%) |
|---|---|---|---|
| longissimus capitis | 90 | 160 | 70 |
| longissimus cervicis | 90 | 160 | 70 |
| longus capitis | 90 & 200 | 100 & 260 | 10 & 60 |
| longus colli | 180 | 250 | 70 |
| scalenus anterior | 180 | 250 | 70 |
| scalenus medius | 180 | 250 | 70 |
| scalenus posterior | 180 | 250 | 70 |
| semispinalis capitis | 90 | 160 | 70 |
| semispinaluis cervicis | 90 | 160 | 70 |
| spinalis capitis | 90 | 160 | 70 |
| spinalis cervicis | 90 | 160 | 70 |
| splenius capitis | 90 | 160 | 70 |
| splenius cervicis | 90 | 160 | 70 |
| sternocleidomastoid | 180 | 250 | 70 |
| trapezius | 90 | 160 | 70 |




Figures 3 A through F **:** Comparison of model response to test data from NBDL

5. DISCUSSION

Figures 3A through 3F show very good correlation between the head/neck model and the NBDL data from time zero to full flexion (approximately 150 ms) and through head rebound.

It could be hypothesized that in flexion the only muscles that are being loaded are the extensors. To a great extent this was true. But, with the onset of acceleration the head rotated forward, loading the extensors, and translated along the axis of the neck, which elongated the neck muscles. To a smaller extent, certain flexors were loaded because of the lengthening. Using muscle length to trigger activation/deactivation allowed for individualized muscle activation/deactivation schemes that can account for such variations.

Activating the contractile element of the muscle with respect to muscle length correlated to the extensor muscles activating 90 ms after the onset of sled acceleration. This translated into a 90 ms reaction time. Reid [12] and Forssberg and Hirschfeld [6] measured neck muscle reaction times as approximately 90 ms, and within a range of 75 to 120ms, respectively. Activation based on muscle length correlated well with that of reaction times.

When an activated muscle began to decrease in length, it deactivated. As the head rebounded into extension, the flexors were lengthened, and therefore activated. If the extensors remained fully active, they would restrict the head to a fully extended position and not allow for proper rebound. Therefore, the extensor deactivation/flexor activation scheme was necessary to appropriately model the head/neck rebound.

6. CONCLUDING REMARKS

A computer model of the human head and neck incorporating active and passive muscles was developed and validated against dynamic experimental data. The model was implemented using the commercial analysis program MADYMO. The active muscles were modeled to include:

- Variable and dynamic activation of muscles based on muscle length.
- Variable and dynamic muscle deactivation based on muscle length.
- Activation and deactivation of flexor as well as extensor muscles.
- Simulation and validation beyond full flexion of the neck and during rebound (up to 300 ms after onset of sled acceleration).

Thanks to these features, the model produces simulation results that are consistent with published data in the “high g” horizontal input acceleration range. Moreover, because of the presence of the deactivation feature, the model is able to capture the rebound of the head, and its simulation output compares well to experimental results in the 200 ms to 300 ms range after the onset of sled acceleration.

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